The Effect of El Niño Southern Oscillation (ENSO) on World Cereal Production

A thesis submitted in partial fulfilment of requirements for the degree of Master of Philosophy in the Faculty of Agriculture and Environment at The University of Sydney

Maryam Abdolrahimi

May 2016

Declaration

This thesis is submitted to the University of Sydney in fulfilment of the requirements for the Master of Philosophy.

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Maryam Abdolrahimi

May 2016

Thesis Abstract

El Niño Southern Oscillation (ENSO) anomalies are responsible for medium-frequency climate fluctuations across many regions of the world. Not only ENSO induces temperature and precipitation variability in the affected regions, but it is also responsible for larger magnitude weather anomalies, such as droughts, hurricanes, and tsunamis. All these directly impact agricultural production. The overall objective of this research is to determine the relationship between ENSO and world major cereal production. While several studies have addressed the issue, this research contributes to the literature in a number of directions. Firstly, it measures the ENSO effect net of temperature and precipitation. Secondly, it allows for the threshold-like effect of ENSO; that is, El Niño effects are not mirror images of La Niña effects. Thirdly, it incorporates expected price in the regression setting, thus controlling for an important economic variable affecting crop supply. Finally, this study applies the largest possible panel of countries, to analyse the region-specific peculiarities of the ENSO–production relationship, and to best approximate the global production effect of ENSO anomalies.

This study uses a combination of extensive climatic and economic datasets spanning the years 1962-2009 to empirically measure the impact of ENSO on wheat, maize and rice production, via a threshold regression framework. The results reveal statistically significant and economically meaningful ENSO impact on cereal production in many regions, with particularly strong effects in Southeast Asian and American countries. Although the expected global effect may camouflage the country-specific effects, the research findings suggest that El Niño shocks are likely to cause on average a reduction in global production of rice and maize. La Niña episodes, on the other hand, are associated with increased global rice and decreased global wheat and maize production.

Although consequences of ENSO shocks on a global scale are sporadic, understanding the overall impact of ENSO on major grain production is an important tool for managing global food security. Results of this study provide implications for food policy makers, and help them develop precautionary economic policies that will take advantage of ENSO signals to cope with production shocks and ensure food availability, which is particularly relevant in the developing world.

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Dr. David Ubilava, for his continuous and generous scientific, practical and emotional support throughout my candidature. This work would not have been possible without the help and support of my supervisor. Many thanks must go to my auxiliary supervisor, Associate Professor Tihomir Ancev, for his support and friendship.

The University of Sydney has provided me with a comfortable environment to work in, and I am especially grateful to the staff of the Faculty of Agriculture and Environment, supportive friends and inspiring colleagues.

Finally I am thankful to my family, especially Hesam, my lovely husband. I really appreciate his encouragement, support and patience.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Climate change and anomalous weather conditions have become a major global concern in recent decades. Among a wide range of possible consequences of climate anomalies, inter-annual variability of agricultural crop yield, hence crop production, is particularly noteworthy, as it is directly influenced by weather conditions in all environments. This arises from the intrinsic impact of weather on plant generative and vegetative growth period. Because agriculture is one of the important economic sectors, links between climate variability and agricultural productivity have broader economic implications. A concept that has already been emphasized in the writings of the Ancient Greeks (Gates 1967). The idea that climatic factors impact on economic performance is sensible, at various stages of product supply, marketing (storage and distribution), economic growth, even health, or social unrest (Hsiang, Meng et al. 2011, Hsiang and Burke 2014). There is a reasonable causal relationship between climatic effect and crops production, and food prices (Bellemare 2015). Accordingly, agricultural activity and decision making must consider climate information (Sreenivas, Reddy et al. 2008, Das and Stigter 2010) to develop temporary economic policy efficiently. Providing storage reserves, cropping pattern variation, crop insurance and tax or subsidies policy are some strategies to cope with climate variability risk.

A plethora of studies suggest that in the course of the ongoing climate change, catastrophic weather events are more likely. In turn, extreme weather conditions in many parts of the world are associated with a medium–frequency[1] climate anomaly known as El Niño-Southern Oscillation, or simply ENSO. “The most dramatic, most energetic, and best-defined pattern of inter-annual variability is the global set of climatic anomalies referred to as

---

[1] i.e., cyclical behaviour that repeats itself every several years.

(El Niño and the Southern Oscillation) ENSO" (Hammer, Hansen et al. 2001). ENSO is a naturally occurring phenomenon with significant impact on the worldwide climate (Ropelewski and Halpert 1987, 1996). ENSO could have positive and negative effects on society and environment; meanwhile to a greater extent of disadvantageous impacts (Hilario, de Guzman et al. 2009). ENSO related pervasive anomalous weather is one of the most critical topics faced by agriculture. The ENSO cycle could affect agriculture via the following: (i) effect on crop production due to the influence of ENSO in temperature and precipitation (Naylor, Falcon et al. 2002); (ii) pest damage because of providing the conditions for the growth of fungi and insects in weather conditions during ENSO event (Rosenzweig, Iglesias et al. 2000); (iii) ENSO-induced hazardous weather conditions like severe drought, flooding and storms (Changnon 1999).

The overall objective of this research is to determine the relationship between climate extremes, associated with ENSO cycle, and world major grain production. In years when severe droughts occur in major food-producing countries, crop losses can affect the global food supply. Any deterioration in a staple crop production would acutely have a negative effect on food security. Understanding ENSO-induced global production shocks can provide beneficial means to improve food security (Gommes, Bakun et al. 1998) and famine deterrent policies.

1.1 El Niño and the Southern Oscillation

The acronym ENSO is an aggregate of a naturally occurring two-way interaction between the ocean (El Niño) and the atmosphere (Southern Oscillation) in the tropical Pacific Ocean (Hilario, de Guzman et al. 2009). El Niño is an event with anomalous appearance of warm sea surface temperatures (SST) in the central and eastern equatorial Pacific Ocean.

Southern Oscillation (SO) is an atmospheric pressure oscillation between the central/eastern Pacific and the western Pacific. These two aspects of the same coupled ocean-atmosphere phenomenon (Bjerknes 1966, Bjerknes 1969) are highly correlated (Trenberth and Hoar 1996). In turn, the El Niño-Southern Oscillation is the most significant climate system correlated with year-to-year weather variability and violent events (Bouma, Kovats et al. 1997). This altering re-occurring interaction leads to extensive repartition of key rainfall-producing system (Rasmusson and Carpenter 1983, Allan 2000).

ENSO is the second most important source of weather variation which creates considerable share of short term climate variation around the world, just following the seasonal cycle (Glantz 2001, Rosenzweig, Iglesias et al. 2001, Goddard and Dilley 2005). In some regions, ENSO explains almost 50 percent of the total variation in local weather (IRI (a)). Among all climate events, ENSO is distinctive for its intensity, predictability and universal effect (McPhaden, Zebiak et al. 2006). The most direct influence of ENSO on regional climate patterns are observed in the nearest area to the tropical Pacific. However, signals of its effect can transform global seasonal temperature and precipitation (Kiladis and Diaz 1989, Vedwan and Broad 2003). These shifts, known as teleconnections (Trenberth, Branstator et al. 1998), arise from the affection of the upper atmosphere from tropical sea-surface temperatures (Fedorov and Philander 2000).

To summarize, ENSO is a climate phenomenon with a genesis region in the Pacific Ocean but has far-reaching consequence for worldwide weather, and is particularly linked with droughts and floods (Kovats, Bouma et al. 2003). There are three ENSO phases known as El Niño (warm tropical Pacific SSTs), La Niña (cold tropical SSTs) and Neutral (non El Niño or La Niña) (Chen, McCarl et al. 2001, Hanley, Bourassa et al. 2003). Every episode has a dissimilar well-defined character (Trenberth and Stepaniak 2001) that vary from relative strengths, maturity, season inception and ending, duration and spatial extent of SST anomalies peak in the tropical Pacific (Lyon and Barnston 2005). El Niño and La Niña demonstrate mirror extremes of the ENSO event. During El Niño, global temperature increase 0·5ºC on average (Kovats, Bouma et al. 2003), however precipitation variances are heterogonous (Ropelewski and Halpert 1987). In general, El Niño (La Niña) phases are associated with a warming (cooling) temperatures in the tropical Pacific and Indian Ocean that attenuate (intensify) precipitation in the western (eastern) Pacific area (Allan, Lindesay et al. 1996).

A number of severe and prolonged ENSO events have been recorded in the late 20th century (Trenberth and Hoar 1996), as well as the two most extreme El Niños (1982-1983, 1997-1998) and La Niñas (1988-1989, 1973-1974) (Gergis and Fowler 2009). The historical incidence of El Niño events indicate that occurrences have been more powerful and repeated since the 1980s, a pattern likely connected to global warming (Timmermann, Oberhuber et al. 1999, Trenberth 1999). ENSO events influence almost every aspect of human society: disease outbreaks (Kovats 2000, Kovats, Bouma et al. 2003), natural disasters (Dilley and Heyman 1995, Ward, Jongman et al. 2014), energy demand (Collins 2007), availability of water resources (Kahya and Dracup 1993, Chiew, Piechota et al. 1998, Barton and Ram ı ́ rez 2004), forest fires (Kitzberger, Swetnam et al. 2001, Siegert, Ruecker et al. 2001), animal movements (DeLong and Antonelis 1991, Paxton, Cohen et al. 2014), fishery catch fluctuations (Johnson 1988, Garcia, Vieira et al. 2003), low and high agricultural yields (Selvaraju 2003, Izumi, Luo et al. 2014), price fluctuations (Keppenne 1995, Ubilava and Holt 2013), the economic welfare (Chen, McCarl et al. 2002, Cashin, Mohaddes et al. 2014), and many others (Wootton, Power et al. 1996, Aguilar and Vicarelli 2011, Bayer, Danysh et al. 2014, Danysh, Gilman et al. 2014). Given the global importance of ENSO, the World

Meteorological Organisation (WMO) updates meteorological and oceanographic data on a quarterly basis to monitor and forecast ENSO episodes, in association with the International Research Institute for Climate and Society (IRI) and about 28 leading centres around the world.

1.1.1 Background of ENSO

In the 1500s fishermen of Peru and Ecuador begun to observe an unusual warming of sea water along the coastal areas around winter time, which would repeat itself every few years (O’Brien, Zierden et al. 1999). Normally sea surface temperature off Peru coastal is colder than in the equatorial region. This is for the northward-moving Peru current that push back the surface water offshore. The upwelling of the nutrient-enriched cold water is an appropriate source for fish also a basis of Peruvian anchovy fishery affluence (Ramage 1986). At the beginning of each year, a warm southward current modified the cool waters. Fishermen usually took benefit of this interval to repair their equipments (Wallace and Vogel 1994). Every few years, however, this anomalous warming would start earlier than expected, extend into early summer (Wallace and Vogel 1994), and lasted over a year (Ramage 1986). Unusual warm waters flowing south increased the sea-surface temperature significantly and fish population declined due to the undiserable temperature and lower nutrients (Ahrens 2012). Further, the Peruvian geographers observed the stronger onset of the warm period that was parallel to an extraordinary oceanic and climatic occurrence in some years (Wang and Picaut 2004, Wang and Fiedler 2006). Since this phenomenon occurred around Christmas, the term El Niño (Spanish for "the Christ Child") was coined by fishermen (Wallace and Vogel 1994, Trenberth 1997, Glantz 2001) at the end of 19th century (Wang and Picaut 2004). With the arrival of foreign scientists to Peru in early 20th century, the identification of ENSO begun in the world's scientific society (Lobell 1942). Thereafter, they recognized El

Niño as a far-reaching event in related to the tropical Pacific ocean warming (Wang and Picaut 2004).

Towards the end of the 19th century, Hildebrandsson realised an osciliation at the western and eastern Pacific atmospheric pressure (Holton, Dmowska et al. 1989). Later, Lockyer and Lockyer (1902a) declared the duration of 3.8 years for this fluctuation. Using data from 95 stations convinced them that fluctuation was almost worldwide (Lockyer and Lockyer 1902b, Lockyer and Lockyer 1904). The occurrence of the violent famine during 1876-1900 caused 25 million fatalities and induced British scientist to investigate the reason of the Indian monsoon rainfall failure (Koutavas 2011). In 1904, Sir Gilbert Walker, a British mathematician started working with British Colonial Service as a Director General of the meteorological observatory. To find out the reason for Asian monsoon oscillations, he classified world weather records associated the sea level pressure fluctuations between South America and India-Australia. He observed a "transpacific linkage of atmospheric pressure systems" (Ramage 1986) which he referred to as a Southern Oscillation (Walker 1924). He found that outstanding global climate variations occurs every few years were correlated with the Southern Oscillation (Walker 1923). The Southern Oscillation is a large scale see-sawing in atmospheric pressure of tropical sea level between the eastern and western sides of the Pacific. Additionally, monsoon precipitation variation connection with Southern Oscillation was defined by Walker and Bliss (Walker and Bliss 1932).

Typically, in the south central Pacific, the sea level pressure (SLP) is relatively high compared to the Indian Ocean and the Northern Australia region, along with the easterly trade winds, a net air movement at low latitude from east to west. Every few years the weakening of the sea level pressure difference between east and west caused relaxed trade winds, leading to drought conditions in the western Pacific region. Walker determined the

Southern Oscillation Index (SOI) to quantify the event. SOI is defined as the difference of sea level atmospheric pressures between the western and eastern Pacific (Ramage 1986). Barometer data records in this region date back to the 1880's (IRI (b)).

After 1950-60s scientist became aware that El Niño was not just a coastal phenomenon in Peru (Wang and Picaut 2004, Wang and Fiedler 2006). Although the warming originates in the tropical Pacific Ocean, progresses westward along the equator (Wang and Fiedler 2006). Jacob Bjerknes (1969) acknowledged that El Niño and Southern Oscillation are oceanic and atmospheric aspects of the same phenomenon (ENSO) (Rasmusson and Wallace 1983, Wang and Picaut 2004, Wang and Fiedler 2006). He revealed the connection of ocean warming and Southern Oscillation (Ramage 1986). Primary means of this connection identification was El Niño based studies at late 1950s relying on conventional merchant ship data (Rasmusson and Wallace 1983). A review of the 1957-1958, 1963-1964, 1965-1966 of El Niño and Southern Oscillation data by Bjerknes confirmed the large scale ocean-atmosphere interaction in the eastern side of tropical Pacific (Rasmusson and Wallace 1983, Wang and Fiedler 2006). For the first time, satellite imagery was applied to determine the central and eastern equatorial region, which faced atypical heavy rainfall during warm sea-surface temperature event (Rasmusson and Wallace 1983). Bjerknes found that SST anomaly following rainfall variation is related to equatorial trade wind transformation. Following Bjerknes, Wyrtki (1975) developed a new framework about El Niño onset. He made use of extensive record of tide gauges to monitor tropical Pacific sea level (Wyrtki 1961, Wyrtki 1977). Wyrtki recognized that El Niño is enforced by sea level heights variation through the expansion of a countercurrent (Wyrtki 1977).

ENSO study was not seriously considered until 1982-83 extreme El Niño. Lack of recognition of this severe warm phase up to the full evolution motivated the tropical climate research community to investigate of ENSO identification and forecast (Wang, Deser et al. 2012). In this regard, the Tropical Ocean Global Atmosphere program (TOGA), as a part of the World Climate Research Programme (WCRP), focused on ENSO study from the early 1980s to mid-1990s. There was a budding interest in ENSO studies during that era and significant progress performed, including robust definition of worldwide ENSO-induced precipitation (Ropelewski and Halpert 1987, Ropelewski and Halpert 1989) and temperature (Halpert and Ropelewski 1992) distribution, determine the first deterministic forecasting model to predict an El Niño event (Cane, Zebiak et al. 1986), set up observing system to monitor and predict ENSO (Hayes, Mangum et al. 1991, McPhaden, Busalacchi et al. 1998) and great improvement in ENSO cycle knowledge and its global teleconnections (Neelin, Battisti et al. 1998, Trenberth, Branstator et al. 1998).

Subsequent to 1997-98 El Niño, which is the most sever in the 20th century (McPhaden 1999, Hossain, Alam et al. 2000), the world's attention was drawn to this phenomenon and its global impact. It was a turning point in studies documented the ENSO. In a way that, more than half of the related literatures since 1966 have appertained to 2000-2005 (McPhaden, Zebiak et al. 2006).

1.2 Quantitative evaluation of ENSO anomalies

Zopf, Short et al. (1978) determine the first quantitative ENSO definition. They classified ENSO events according to the strength and onset time as strong, moderate, weak, or very weak. The widely used indices that typically applied to categorize El Niño or La Niña events consist of:

- Southern Oscillation Index (SOI) derived from surface atmospheric pressure
- Sea surface temperature (SST) across the Pacific Ocean.

The SOI and SST indices each describe ENSO events in phase and intensity.

1.2.1 Southern Oscillation Index

SOI is calculated from the monthly or seasonal fluctuations in the surface air pressure between Tahiti and Darwin. Sustained negative (positive) SOI values below (above) -8 (+8) indicate an El Niño (La Niña) (Australian Bureau of Meteorology). SOI values and the El Niño and La Niña phases are illustrated in Figure 1.1. Since the SOI value can indicate local weather anomalies, major phenomenon usually measured using 5-month mean (IRI 2015b). Since the SOI measurement is based on two different locations with varying conditions, it is considered as a noisy index (Meyers, O'Brien et al. 1999).

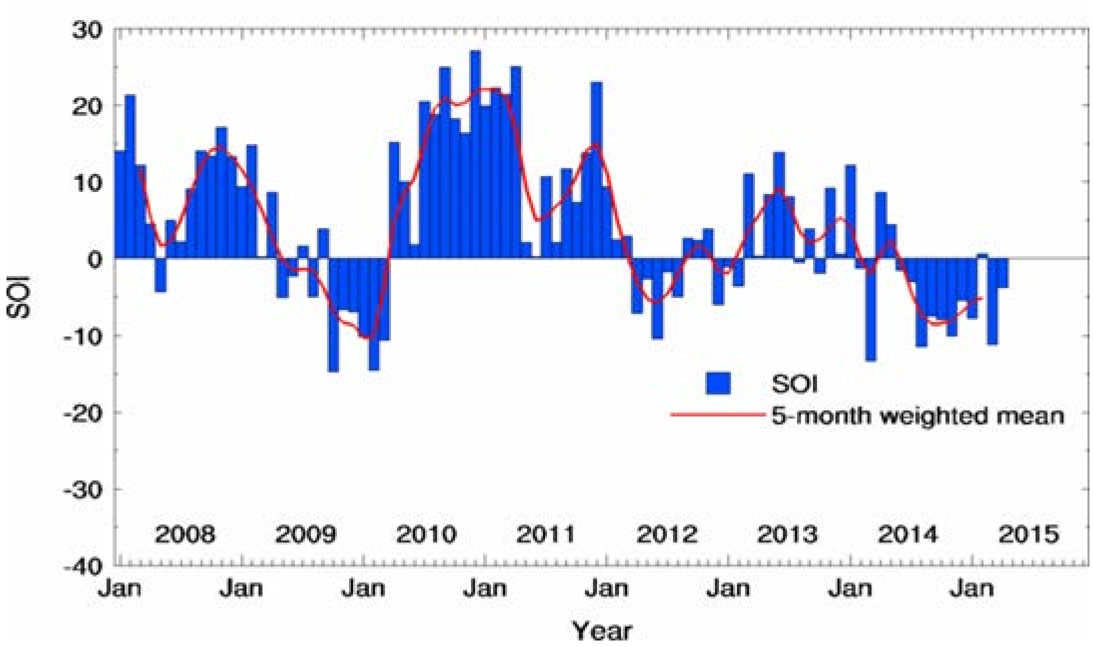

Figure 1.1. Southern Oscillation Index (monthly values and five-month weighted mean).

Source:(Australian Bureau of Meteorology)

1.2.2 Oceanic index

The temperature-based index measures the average sea surface temperature anomaly (SSTA) over different areas of the Pacific Ocean (Table 1.1 and Figure 1.2). SSTA is the difference between the real SST and the climatological one. The observed SST comes by the Tropical Atmosphere Ocean (TAO) array data which is collected from a network of about 70 deep-ocean buoys in the equatorial Pacific Ocean (Coles 1999). Sea surface and sub-surface temperatures transmission, atmospheric status, water currents and wind data are recorded by the buoys in the different regions. Values are derived using a real mean standardized anomaly of SSTs from a prescribed climatological period.

Table 1.1. The latitude and longitude ranges of particular region for SST indices

Index	Latitude	Longitude
Niño1+2	0°-10°S	90º-80ºW
Niño3	5°N-5°S	150º-90ºW
Niño3.4	5°N-5°S	170º-120ºW
Niño4	5°N-5°S	160ºE-150ºW
JMA	4°N-4°S	150º-90ºW

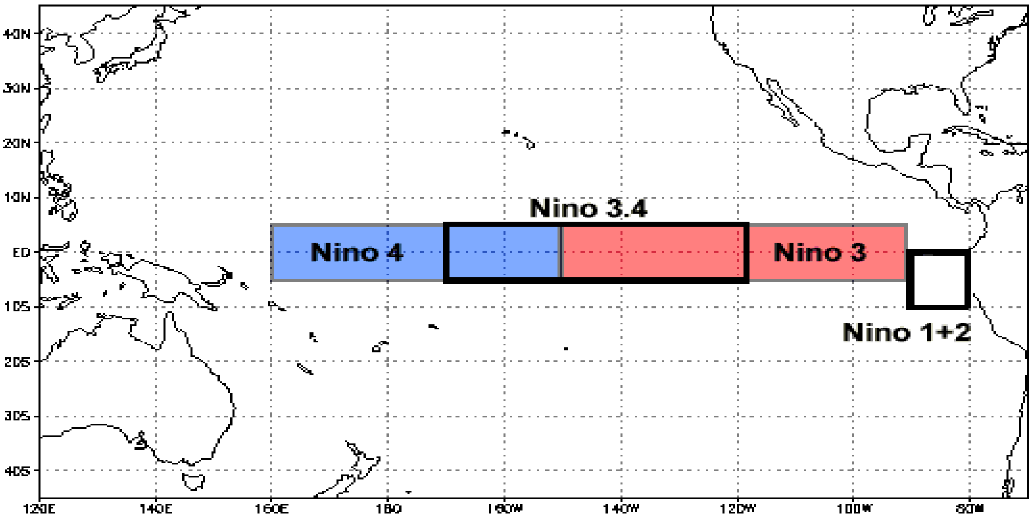

Figure 1.2. Areas in the Pacific Ocean over which sea-surface temperatures are averaged for Niño indices.

Source:(NOAA)

The Niño1+2 region (along the west coast of South America) is the first to get warm (IRI 2015b), which is quick to react to seasonal and El Niño-related variations (Glantz 2001). The temperature variation among Niño3 (east Pacific cold tongue) is more than others (IRI 2015b), while has much less reaction to continental impacts (Hanley, Bourassa et al. 2003). SSTs Shift in Niño4 region (West Pacific warm pool) are connected to changes of intense east-west temperature gradients along the longitudinal equator (Glantz 2001). The level of precipitation in Southeast Asia is explained by Niño4 (IRI 2015b). Niño3.4 (middle of Niño3 and Niño4) SST index is the most commonly used because of the well-captured SST variability and precipitation shift (NOAA, IRI 2015b). Bamston, Chelliah et al. (1997) define Niño3.4 as a stronger representative for ENSO event than Niño3 for being more attached with SOI. The Niño3.4 index has more explanatory power in describing ENSO evolution (Trenberth and Stepaniak 2001) and shows the greatest overlap with event history (Trenberth 1997). The JMA index was assigned by the Japan Metrological Agency. Hanley, Bourassa et al. (2003) Suggest that JMA index should apply in combination with of one of the SOI, Niño3.4 or Niño4 indices.

The El Niño or La Niña classification is based on exceeding SSTAs beyond a threshold in the equatorial Pacific appointed region. SSTAs equal to or greater than 0.5°C in the Niño3.4 region are stating of ENSO warm phase (El Niño) conditions. Anomalies less than –0.5°C are indicative of cool phase (La Niña) conditions (Figure 1.3). This approach of NOAA is the objective procedure in this research. ENSO events that are defined using Oceanic Niño Index (ONI) follow the five consecutive 3-month running mean SST anomalies exceeding the threshold.

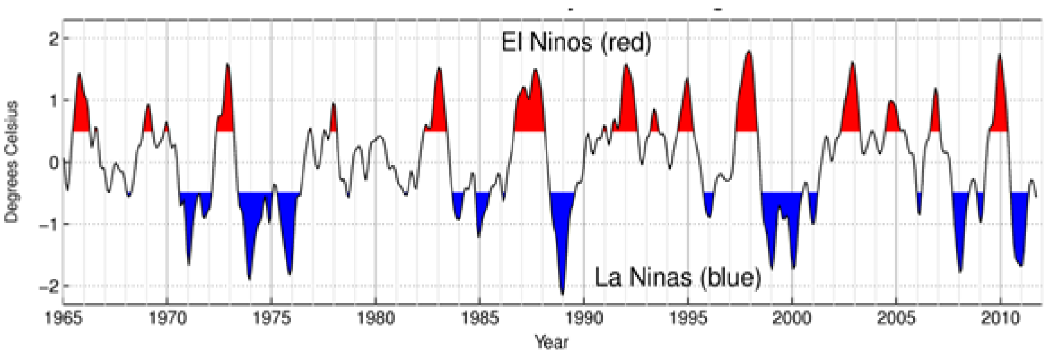

Figure 1.3. Time series plot of SSTA in Niño3.4 region.

Values exceeding threshold of ±0.5°C illustrate ENSO event (Pierce 2011).

1.3 Historical evidences of the relationship between ENSO and global food security

Agriculture has been described as "the most weather-dependent of all human activities" (Oram 1985). Even with recent advances in agricultural technologies, climate and weather are still the key elements in determining productivity because solar radiation, temperature, and precipitation are the most important factors in crop growth (Rosenzweig, Iglesias et al. 2001). Temporal and spatial variance of meteorological conditions and storms can affect soil conditions, water availability, agricultural yields and susceptibility to pest and pathogen infestations.

"Variability in agricultural production affects risk on at least five levels: individual farms, farming regions within nations, nations, groups of nations, and the global food system" (Rosenzweig and Hillel 2008). Food security in different aspects of availability, accessibility, utilization and stability affect by climate (Selvaraju 2011). The livelihood and subsistence of global rural population, containing over 3.3 billion population (World Bank(a) 2016), are directly dependent on agriculture. Corollary, they are the most vulnerable to climatic events (Selvaraju 2011). Annually 2.2 billion tonnes of cereal production supply a significant part of the required food and feed (FAO 2007). Any meteorological disaster could be a significant restricting factor for stable food production.

The forms and level of ENSO impact depend not purely on the length and strength of event, but also on the status, vulnerability and sensibility of affected system, level of population and its biotic community (Rosenzweig and Hillel 2008). The 1972 anomalous climate had a detrimental impact on global food production and food security. The former Soviet Union experienced one of the worst grain production shortfalls due to the intense drought. To recover the grain especially wheat and maize, it resorted to great quantities of import from the U.S. (Glantz 2001, Rosenzweig and Hillel 2008). This, in turn, exacerbated food shortages in the world (Trager 1975). For instance, there was a global shortage of supply in grains, particularly wheat and maize, in the world food market. A severe drought during summer caused a significant reduction in rice production in Southeast Asia, especially in Indonesia, Thailand and the Philippines. Thailand banned rice export and there was no international rice market for nine months (Dawe 2012). In addition, the impact of the 1972-73 El Niño on the Peruvian fish industry deteriorated global food supply. The decline in fish catches was a threat for food security. The scarcity of fish meal and its high price in the market lead poultry industry to the soymeal as a second best substitute. This enticed U.S. farmers to plant soybean instead of wheat. This was done when wheat was in great demand and global food crisis was serious (Glantz 2001). As a result of the climatic fluctuation, global food production per capita and food reserves collapsed for the first time in more than 20 years (Glantz 2001).

The El Niño of 1982–83 was one of the strongest events of the 20th century. It was considered the strongest in more than 400 years at the time (Rosenzweig and Hillel 2008), which caused at least US$13 billion of loss and 1,500 deaths (Pfaff, Broad et al. 1999). In

Peru, “cotton, sugarcane, rice, and potato fields were silted or damaged by erosion” (Rosenzweig and Hillel 2008). Rising staple food prices were to the extent that made them unaffordable for the poor (Cavledes 1985). During the flooding in Brazil, in total, 1.6 million tonnes of crops including maize, soybean, cotton, coffee, potatoes, beans, and rice were damaged. El Niño-related storms in 1983 caused about US$200 million damage in agricultural production in California. Flooding in Mississippi and Louisiana resulted in damage of 120,000 hectares of farmland, 17 percent loss of the cotton crop, death of 100,000 poultry and 1,000 cattle. Maize production in the central U.S. was as half of the previous year that means US$5.5 billion loss. The estimated losses for soybean were US$3.4 billion, for sorghum and tobacco were US$500 million and US$1.1 billion, respectively (Rosenzweig and Hillel 2008).

The 1997–98 El Niño events again shocked the scientific community for their sudden onset and large amplitude (McPhaden 1999). The global economic cost of this was about US$100 billion, also 110 million people affected (RAO 2008). The fishing industry in Peru again disrupted, as well as the transportation systems (Rosenzweig and Hillel 2008). In the southeast South America, rich soil moisture related to a typical wet El Niño phase leads to a record in Brazil and Argentina for soybean crop, whereas in Central America export vegetable production damaged because of drought. The price of national fresh production and strawberries rose 8 percent and 100 percent, respectively (Changnon 2000). Heavy rains and flooding in California, Florida and Arizona caused losses to fruit, vegetable and cotton (Adams, Chen et al. 1999). Estimated El Niño associated total U.S. agricultural losses ranged from US$700 million (Changnon 2000) to US$1.7 billion and US$2.2 to US$6.5 billion loss for La Niña (Adams, Chen et al. 1999).

The El Niño during 1997-98 caused drought in Indonesia which resulted in 3.5 million tonnes cereal shortfall (CARE 1998). Extensive forest fires in late 1997 and early 1998 affected nearly 5.2 million hectares (Siegert and Hoffmann 2000). Rice production reduced as a result of harvest area decrease due to water shortage was estimated about 4 percent. Other food crops production reduced around 4 percent to 10 percent in 1997 and 1 percent to 6 percent in 1998 (Irawan 2002). Rice production decreased simultaneously with the economic crisis, which caused a 300 percent rise in rice prices (Subbiah, Kishore et al. 2001). In South Asia, there was a reduction in coffee and palm oil production which lead to a rise in international prices (Changnon 2000). The El Niño induced heavy rains which destroyed beans and Irish potato fields in Kenya. Banana and root crops damages were in the lowest level (Takaoka 2005). Floods in East and Southern Africa caused large scale crop damage in the field and in stores. In addition, the flooding affected sub-region’s infrastructure, like inundating roads, rail lines, bridges, and disrupted food and non-food items transportation (CARE 1998).

1.4 The significance and objective of this study

The overall objective of this thesis is to estimate the relationship between ENSO and the major cereal producing regions in the world. This study will measure the effect of ENSO on wheat, rice and maize production, in the main producer countries using a regression model, then the ENSO effect on the global-mean production of the considered crops has quantified. The socio-economic importance of these crops in the world is enormous, as cumulatively they account for almost 44 percent of all calories and 37 percent of all protein of the worldwide human diet (Reynolds 2010).

From an agricultural and food security point of view, investigating the potential impact of ENSO on global cereal crops production is important in these respects: (i) What has been the El Niño and La Niña impact on crop production? (ii) Are some countries more vulnerable to this impact than others? In the face of climate anomalies, the level of preparation and reaction of farmers, regional policy makers, inputs suppliers and insurers could influence farm productivity at regional and national levels. The connectivity of the global food system provides an interactive condition such that a negative climatic effect in one region can be mitigated by other regions. Although, limiting outputs and rising commodities price can make a benefit for some regions.

Research relating to the ENSO influence on agriculture has been done principally on a region or country basis and studies about the ENSO impact on global scale are infrequent. Regional research could manifest the production variability and the regional impact comparison can help provide a broader perspective context. But, a global study can provide a clear consistent pattern instead of fragmented elements. Understanding the overall impact of ENSO on global production is an important tool for management food security in the world. In addition, increasing the regional effectiveness of food security management, and in turn, needs a deeper global understanding and international scientific and strategic cooperation.

This study will demonstrate how ENSO event economic consequences can be evaluated by using historical climatological records, including sea-surface temperature, air temperature and precipitation. In this study an econometric models applied to estimate the production variability caused by the El Niño and La Niña phase on various cereals, which constitute a staple food in many diets across the globe. The main feature of this framework is a regression model which consists of climatic and economic variables jointly.

This study offers a comprehensive analysis of literature on topic of economic consequences, and particularly the production impacts of ENSO shocks. Additionally, this research contributes to the ENSO-related literature in a number of directions:

i. Assessing the global effect of ENSO on major crops, net of temperature and precipitation (thus potentially measuring the effects of extreme weather conditions due to ENSO, which tend to be camouflaged in usual weather variables),

ii. Examining the nonlinear (asymmetric) effects of ENSO (thus recognizing that El Niño effects are not mirror images of La Niña effects, and that large ENSO shocks result in disproportionally large production changes,

iii. Incorporating economic variables in the regression setting, such as expected price, (thus controlling for an important economic variable affecting crop supply),

iv. Including the largest possible panel of countries in the study, to analyse the region-specific peculiarities of the ENSO-production relationship, and to best approximate the global production effect of the ENSO anomalies.

1.5 Summary

Climate and agriculture are naturally interdependent. The El Niño Southern Oscillation (ENSO) phenomenon is significantly responsible for seasonal climate fluctuations in many regions of the world. ENSO-related pervasive anomalous weather is one of the most critical issues faced by world economies. The issue is particularly relevant for countries relying on agricultural production as well as food imports. The simultaneity of the ENSO impact in various parts of the world provides a probability of spatial correlation of related effects. This statement is more controversial for leading crops in the western Pacific regional countries and Central and South America western coastal regions. From social and economic standpoints, wheat, maize and rice are the most important crops in the world that provide required components of more than half of diet of the world's population.

The objective of the research is to present a better understanding of the dynamics of ENSO in world wheat, maize and rice production. The motivated points to examine the impact of ENSO cycle on global cereals production are: (i) the importance of these cereals as a main source of food in the world, (ii) the vulnerability of crops to drought, and (iii) concentration of the most key producer where most are affected by the ENSO. Despite the actual well-evidenced ENSO effects on wheat, maize and rice in some of the key countries, there are not many global studies. The effect of ENSO on the economics of cereal production is not broadly assessed. Finding the mechanisms by how ENSO impacts cereal production at a global scale will be crucial for a comprehensive assessment of global food security.

Chapter 2. Review of Literature

The El Niño-Southern Oscillation is the result of the interaction between equatorial sea surface temperature and atmosphere, causing broad climate variation. The El Niño-Southern Oscillation has been developing climate anomalies, especially in the spatial distribution of precipitation. EL Niño phases lead to increased rainfall across the east-central and eastern Pacific and drought in the western Pacific. Typically El Niño makes an expansion in drought condition in East and South Asia, southern Africa and Australia. The last ten most severe El Niños caused widespread drought in China, India, Indonesia, even Brazil and South Africa (Berry and Okulicz-Kozaryn 2008).

Wassmann, Jagadish et al. (2009) demonstrate that drought is a principle climatic variable that leads to yield reduction. Drought is a main source of yield and quality reduction in cereal crop in many of the world’s cereal producing region (Sheng and Xiuling 2004, Bagci, Ekiz et al. 2007, Akanda 2011). Paddy water requirement is high, relative to other cereals (Toole 2002), and is therefore more sensitive to drought. The main constraint factor of rice production in Asia, especially in rainfed areas, is drought (Pandey, Bhandari et al. 2007 a). In Asia 23 million hectares of rice-growing land, including subhumid areas, are frequently affected by drought (Pandey, Bhandari et al. 2007b). Most of the coastal and delta regions in Asia are exclusively allocated to rice cultivation (Wassmann, Jagadish et al. 2009). In addition, these regions are susceptible to severe droughts caused by ENSO (Dawe, Moya et al. 2009).

Much of previous research involving the ENSO effect on agricultural production, has revolved around five general themes: (1) Detecting the occurrence of ENSO and its impact on climate; (2) ENSO-induced effects of inter-annual variation in temperature and precipitation on production; (3) ENSO effect on agricultural commodities prices due to shortage or excess supply; (4) Macroeconomic performance affected by ENSO; and (5) Economic benefits of ENSO forecasting. This chapter is designed to provide a review of the relevant literature.

2.1 El Niño-Southern Oscillation

In the tropical Pacific region, during normal condition, trade winds regularly blow from the eastern Pacific high pressure to the western Pacific low pressure (Figure 2.1). The predominant easterly winds tend to push warm surface water from the eastern and central equatorial Pacific regions (South America coastal regions) toward west (Asia and Australia) and leads to an increase in water temperature due to exposure to the sun. Consequently, the warm surface water along the equator provides increase precipitation in the western Pacific region. Meanwhile, an upwelling in the eastern Pacific region provides cold and nutrient-rich water that supports the fishing industry of South America. In addition, surface water, induced by pressure pattern, causes a rise in sea level in the western Pacific. From the thick layer of warm water in the western Pacific Ocean, a weak current flow along the equator to South America referred to as the “Equatorial Counter Current”.

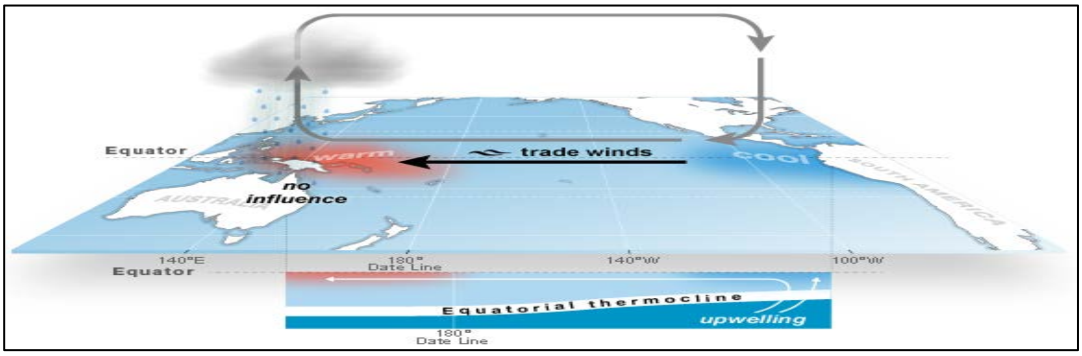

Figure 2.1. Normal contidion in the equtorial Pacific

Source: (Australian Bureau of Meteorology 2012)

Patterns of atmospheric pressure at sea level change periodically; higher in the western Pacific region and lower in the east. This leads to weakened trade winds. During the period of switching between low-and high-pressure systems, westerly winds replace trade winds (Figure 2.2). The atmospheric pressure inversion at the both ends of eastern and western Pacific is referred to as the “Southern Oscillation”. Westerly winds develop an equatorial counter current and push warm water to the eastern and central Pacific regions. This causes an elevation in the eastern Pacific surface. This makes eastern and central Pacific sea surface temperature (SSTs) warmer, relative to normal condition. Anomalous warming in the eastern/central equatorial Pacific sea surface temperature commonly is noted as “El Niño” (Philander 1985). The interaction between warmer SSTs and atmosphere, in turn, further weakens the trade winds. The simultaneity of both anomalies in sea surface temperature (El Niño) and sea level pressure (Southern Oscillation) is the El Niño-Southern Oscillation phenomenon (ENSO). Since, El Niño arises with a great anomaly in the Southern Oscillation; ENSO is the terminology that describes the joint phenomena (Nicholls 1991).

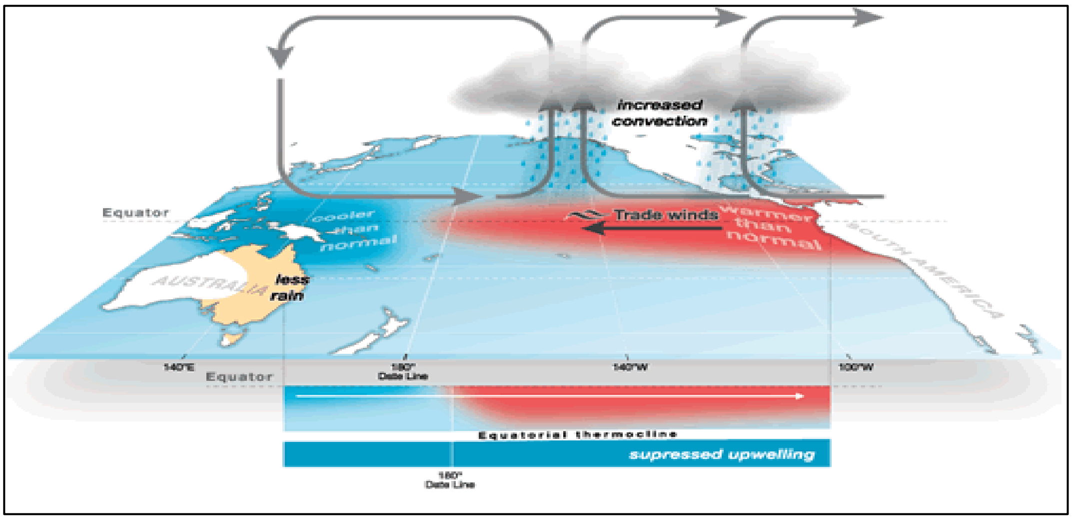

Figure 2.2. El Niño condition in the tropical Pacific.

Source: (Australian Bureau of Meteorology 2012).

The interaction of the alternating warming of sea surface temperature and Southern Oscillation is locally known as El Niño along northern Peru and southern Ecuador coastal region (Trenberth 1997). The ENSO cycle is comprised of three phases: “warm tropical

Pacific SSTs (El Niño), cold tropical Pacific SSTs (La Niña) and near neutral conditions" (Hanley, Bourassa et al. 2003). Oscillations leading to warming of the sea surface are known as El Niño events; those leading to cooling of the sea surface are known as La Niña events. During La Niña (Figure 2.3), the counterpoint of El Niño, intensified trade winds accumulate cold surface water in the western coast of South America. The result is colder-than-normal SST in the eastern and central Pacific. As a result, a thick layer of warm water and heavy rainfall form in the western Pacific regions.

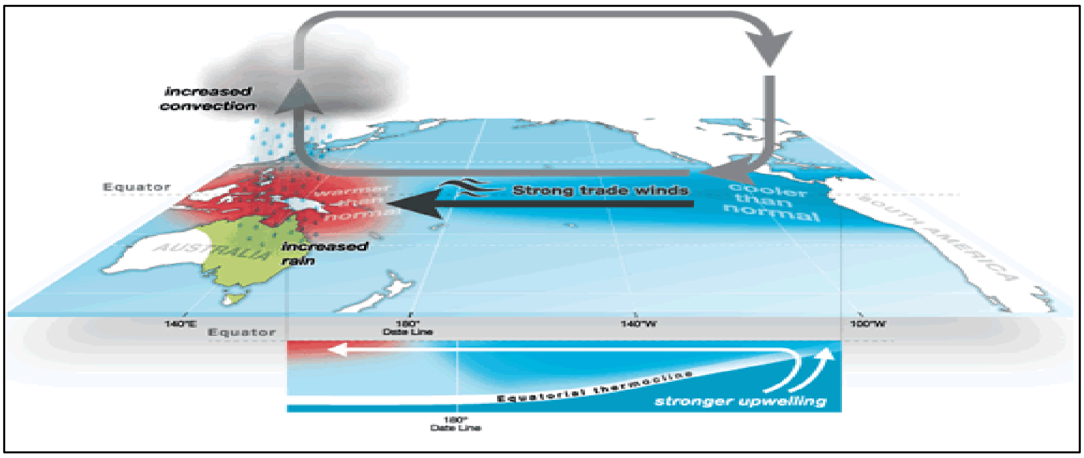

Figure 2.3. La Niña condition in the tropical Pacific.

Source: (Australian Bureau of Meteorology 2012).

The transition between a warm and a cold phase happens through a delayed negative reaction of ocean dynamic regulation (Neelin, Battisti et al. 1998, An and Kang 2000, An and Jin 2001). El Niño cycles typically recur in a time period of two to seven years (Hanley, Bourassa et al. 2003, Wang and Fiedler 2006) and persist for about two years (Brunner 2002). Timmermann, Oberhuber et al. (1999) estimate that the probability of the occurrence of the 3 different phases of ENSO is different and is 0.238 for El Niño, 0.250 and 0.512 respectively for La Niña and neutral phases. However, global climate change may increase the frequency and intensity of ENSO (Timmermann, Oberhuber et al. 1999), between 1976-95 the frequency of El Niño increases, unlike La Niña phase (Trenberth and Hoar 1996). ENSO frequency from once per 8 years during 1876-1976, increases to once per 4 years during 1977-2000 (Irawan 2002).

ENSO is broadly identified as a key determinant of climatic anomalies in the regions adjacent to the Pacific Ocean and even farther regions (Ropelewski and Halpert 1996, Mason and Goddard 2001). Despite the occurrence of ENSO in the tropical Pacific, the global weather and as a result crop production, commodity price, agricultural income or sectoral performance in different part of the world will be affected e.g.(Nicholls 1985, Keppenne 1995, Adams, Chen et al. 1999, Messina, Hansen et al. 1999, Roberts, Dawe et al. 2009, Ubilava and Holt 2013, Liu, Yang et al. 2014).

2.2 The effect of ENSO on world climate

The ENSO cycle has been a feature of Earth’s climate for 130,000 years (Sarachik and Cane 2010). ENSO is accountable for such historical recorded events like biblical droughts in Egypt (Eltahir 1996). El Niño influences the weather near Peru dates back to the year 1525 (Ortlieb 2000). The interactions between ocean and atmosphere in the tropical Pacific region have been linked to climate fluctuations in the world (Ropelewski and Halpert 1987). A great number of studies investigate the relationship between ENSO and rainfall. Ropelewski and Halpert (1987) conducted the most comprehensive one that applied worldwide data from 2000 rainfall stations.

El Niño-Southern Oscillation event can change the weather patterns in more than 60 percent of the world (Kandji, Verchot et al. 2006). Some studies indicate that rainfall and temperature variance patterns are extremely consistent with ENSO index oscillations (Wang and Fiedler 2006, An 2009, Cai and Cowan 2009). Rasmusson and Carpenter (1982) show ENSO-related variation in the tropical region and far-reaching effect in the world. The ENSO effects on the tropics are direct and intense, especially in monsoon-affected countries in Asia, Australia and Africa (Sikka 1980, Holland 1986, Quinn 1987, Janowiak 1988, Kumar, Rajagopalan et al. 1999). In addition, ENSO accounts for a significant proportion of precipitation and temperature changes around the world (Hansen, Jones et al. 2001). The major global El Niño impact is exceeding the mean temperature anomalies above the trend (Salinger 2005). Evidence shows that precipitation in the world is affected by ENSO events, although the extent of the effect differs with region (Waddington 1993, Stone, Hammer et al. 1996). Hsiang and Meng (2015) show +1°C increase in Niño3.4 index results in +0.27°C rise in tropics local temperature and -4.6cm rainfall reduction.

ENSO strength and the severity of effects are linked, however, it is relatively weaker for La Niña events (Lyon and Barnston 2005). El Niño causes an eastward shift in tropical rainstorm pattern, so that, higher than normal air pressure expansion and abnormally dry conditions or drought arise over northern Australia and Indonesia and drier winters in southeastern Africa and northwestern India. Contemporary, in the central and eastern Pacific and west coast of South America rainfall level excessively elevate (Salinger 2005). In general, droughts in the western Pacific, more than normal rains over equatorial coast of South America and the occurrence of storms and hurricane in the central Pacific are an El Niño-induced global climate variation (Cashin, Mohaddes et al. 2014). Almost opposite patterns happen during La Niña event (Salinger 2005). The global climatological effects of an El Niño and La Niña event are summarized in Figures 2.4-2.7.

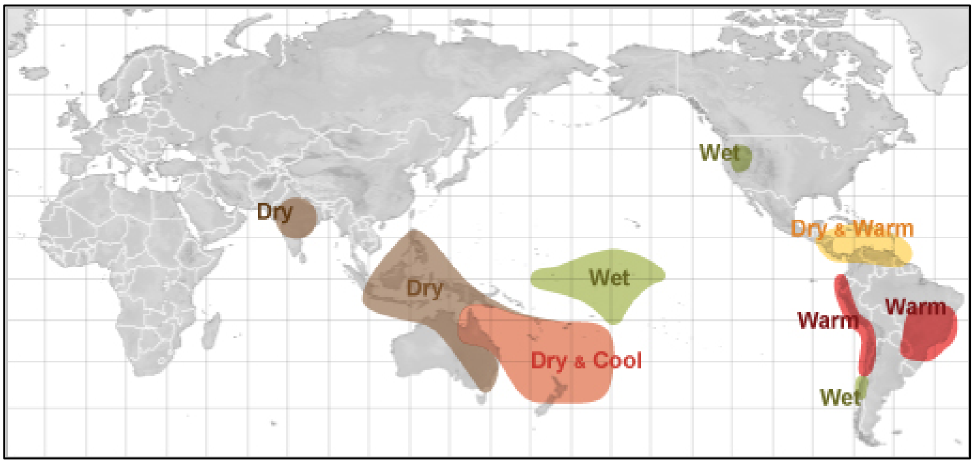

Figure 2.4. Typical rainfall patterns in El Niño events during June through August.

Source: (NOAA 2014).

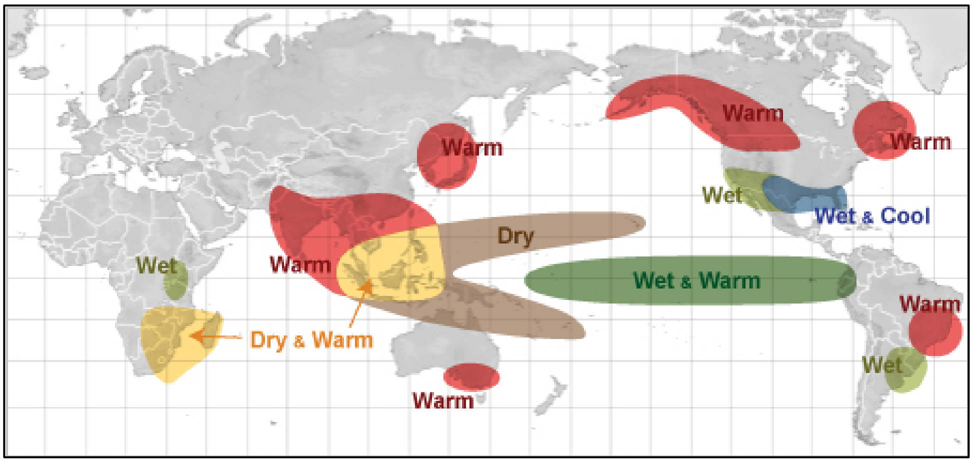

Figure 2.5. Typical rainfall patterns in El Niño events during December through February.

Source: (NOAA 2014).

Given the important role of rainfall as the primary source of soil moisture (Krishna Kumar, Kumar et al. 2004, Sivakumar, Das et al. 2005, Lobell and Burke 2008, Rosenzweig and Hillel 2008) and temperature (Wheeler, Craufurd et al. 2000, Luo 2011) in crops productivity, the following section will review the ENSO influence on precipitation and temperature. Since ENSO-induced rainfall variability is more effective on yield level (Shuai, Zhang et al. 2015). Consequently, there is a greater focus on rainfall variation.

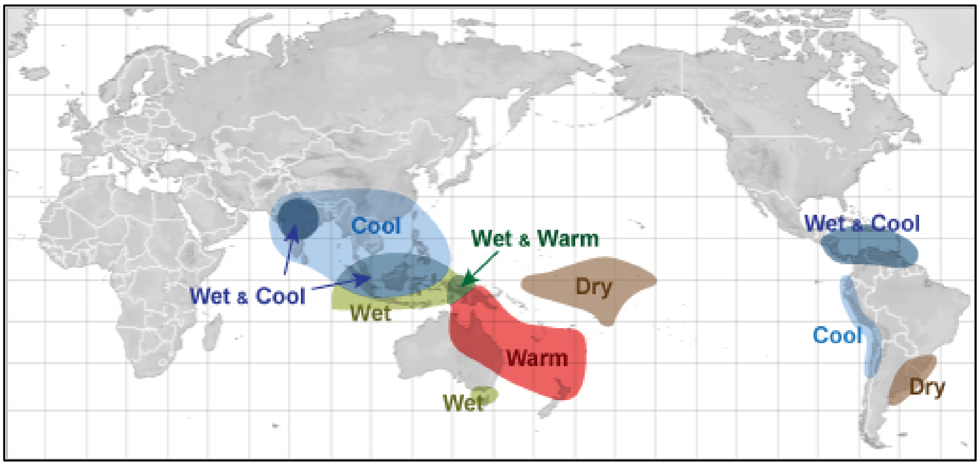

Figure 2.6. Typical rainfall patterns in La Niña events during June through August.

Source: (NOAA 2014).

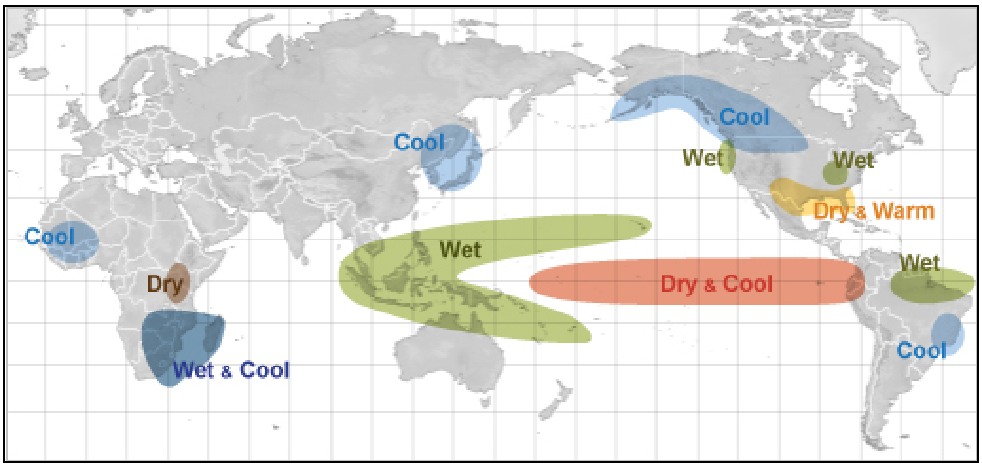

Figure 2.7. Typical rainfall patterns in La Niña events during December through February.

Source: (NOAA 2014).

2.2.1 Asia

In east and south Asia, annual rainfall variations are associated with ENSO (Kinter III, Miyakoda et al. 2002, Hu, Wu et al. 2005). Strong El Niño events cause severe drought in Southeast Asia (Enfield 2003). Naylor, Falcon et al. (2001) find that May-August SSTAs in Niño3.4 region are negatively linked with September–December rainfall in Indonesia. Also, Naylor, Falcon et al. (2002) show that Niño3.4 SSTAs variations are highly associated with changes in September–December rainfall in Indonesia. Long run time series data from 1830 to 1953 indicate that 93 percent of dry years in Indonesia have coincided with El Niño events (Quinn 1987). In the Philippines, El Niño events cause a decline in rainfall (Trenberth 1997), versus La Niña events (Harger 1995). Some evidence has demonstrated the ENSO effect on rainfall in Sri Lanka (Kane 1998, Punyawardena and Cherry 1999). There is a negative association between El Niño and rainfall in one of the two primary rice growing seasons in Sri Lanka (Zubair 2002). El Niño and Indian monsoon are highly-correlated (Parthasarathy, Munot et al. 1988, Webster and Yang 1992, Webster, Magana et al. 1998), 72 percent of drought years of Indian summer monsoon rainfall are linked with El Niño (Varikoden, Revadekar et al. 2014). El Niño events are associated with droughts and La Niña with floods in India, but with a distinctive spatial distribution (Varikoden, Revadekar et al. 2014). Jintrawet and Buddhaboon (2011) find that El Niño events have a negative effect on annual rainfall in Thailand. ENSO covers almost half of the rainfall variations of China in 1997 and 1998 (Lau and Weng 2001). Zhang, Sumi et al. (1999) investigate the effect of ENSO events on rainfall in different seasons of China and conclude the impact of ENSO varies in different seasons and areas. The results indicate that El Niño in its mature phase affects precipitation significantly, in China. The negative impact appears in the southern and northern regions of China, and the positive impact is in between. Tao, Yokozawa et al. (2004) declare during La Niña years summer mean temperature in northern China increases more than 1ºC, compared to normal years. Also, summer rainfall in northwestern China decreases during El Niño, whereas, it increases in southern provinces during La Niña events. Nazemosadat and Cordery (2000) found the Southern Oscillation and autumn rainfall in Iran are negatively correlated. The monsoon rainfall in Nepal, containing 80 percent of the annual rainfall, and SOI are highly positive correlated (Shrestha 2000). In Pakistan, monsoon rainfall is lower than normal in El Niño years and rainfall reduction is highly significant during July-September. In addition, summer monsoon rainfall intensifies in the year immediately after El Niño event

(Mahmood, Khan et al. 2004). Analysis of rainfall time series data during 1950-1992 in Bangladesh finds a tendency of reduction about 70 percent in El Niño years (Hossain, Alam et al. 2000).

2.2.2 America

Ropelewski and Halpert (1987) and (1989), were the first, to find the ENSO-induced temperature and rainfall variation in southeastern South America (Argentina, Brazil, Uruguay). Warm phase of ENSO presents positive rainfall anomalies during November–February and cold phase causes less than normal rainfall during June-December. Grimm, Ferraz et al. (1998) state the anomaly level is larger in Uruguay than Argentina and Brazil. There is evidence that ENSO affects rainfall during November–February, in lower extent, and during October–December in southern Brazil and Uruguay (Diaz, Studzinski et al. 1998). Podesta, Letson et al. (2002) declare Argentina confronts with more rainfall than average during El Niño events, unlike La Niña. Wet summer during El Niño years that results in soggy fields in Argentina and extremely dry summer causes drought during La Niña years (Penalba and Robledo 2005, Pol and Binyamin 2014). El Niño events are associated with lower temperature in the southeast U.S. winter (Green, Legler et al. 1997). Izaurralde, Rosenberg et al. (1999) show the temperature and rainfall deviation of a moderate and strong El Niño event from normal condition in North America. They outline that, winters are warmer during both cases of El Niño; apart from the eastern U.S. (in moderate El Niño) and tropical Mexico regions (in strong El Niño). Warmer spring and summer seasons happen during a moderate and strong El Niño event, but not in subtropical Mexico and the U.S. (just in spring of strong El Niño). Except from Canada and Mexico (under moderate El Niño phase), temperature decreases in northern America during autumn. There is less than normal rainfall in summer in the U.S. and in autumn in Canada during typical El Niño event. Winter rainfall reduces in Canada, subtropical Mexico and the U.S. Corn Belt in moderate El Niño event. In spring of a moderate El Niño, rainfall increases in Mexico and decreases in other regions. During strong El Niño, spring is wetter than normal years, except for Canada. Phillips, Rajagopalan et al. (1999) show summer temperature and rainfall in the U.S. Corn Belt are negatively and positively associated with Niño3 index, respectively.

2.2.3 Africa

The typical rainfall anomaly due to ENSO is a dipole rainfall pattern over Africa: Rainfall in northern and southern Africa is negatively associated with equatorial SSTA, whereas rainfall in eastern Africa is positively correlated with equatorial SSTA (Nicholson and Kim 1997, Camberlin, Janicot et al. 2001). Rainfall of the second half of the year represents the strongest correlation, and April–May season has the lowest correlation (Camberlin, Janicot et al. 2001). ENSO-related impact is more intense in eastern equatorial and south-eastern Africa (Nicholson and Kim 1997). Much of southern Africa observed drier than normal conditions during El Niño event (Mason and Tyson 2000, Mason 2001). Drought occurs mostly in December to March duration after El Niño onset (Ropelewski and Halpert 1987). Also, there is 120 percent increase in the probability of the drought during El Niño (Thomson, Abayomi et al. 2003). On the other hand, in east Africa, the equatorial belt, flood occurrence is more likelihood during short rainy season (October-December) in warm phase of ENSO (Indeje, Semazzi et al. 2000, Philippon, Camberlin et al. 2002). Joly and Voldoire (2009) show Sahelian rainfall is statistically impacted by developing phase of ENSO, so that it is negatively associated with equatorial Pacific SSTA. El Niño events elevate the probability of drought occurrence in Sahel (Rowell 2001). Totally, northeastern and southern tropical climate regions in Africa are negatively linked to Niño3 index. This is relevant for Sahel rainfall and western Africa (Parts of the Gulf Guinea area). However, it is not significant for northern summer season in last mentioned region (Camberlin, Janicot et al. 2001).

Receiving below than normal rainfall region in southern Africa during El Niño events is the belt that expands from east in southern/central Mozambique to west in Namibia, also the western half of South Africa. Rainfall decrease is more frequently in southern Mozambique, northern South Africa, eastern Zimbabwe, northern Namibia, and northern Botswana (USAID 2014). In Madagascar, drought and wildfire happen in El Niño years (Philander 2008), or after El Niño events (Ingram and Dawson 2005). Cane, Eshel et al. (1994) show the strong link between rainfall in Zimbabwe and contemporary SSTA in Niño3 region, as well as, between a lead time of more than one year. Also, Phillips, Cane et al. (1998) find that seasonal rainfall during El Niño phase is less than of, both, normal and La Niña years in Zimbabwe. Wang and Fiedler (2006) observe the dry and wet spell frequencies in Zambia and Niño3.4 SST index are highly linked. El Niño years increase dry spell over Zambia during rainy season (December-February). During La Niña years, Zambia benefits from favourable rain. The History of ENSO event during 1972–2002 indicates that 92 percent of El Niño years were associated with moderate, extreme or severe drought in Nigeria. Onset and termination of rainy season is later and earlier than normal years, respectively (Ati, Iguisi et al. 2010). Main rainy seasons (JJAS) in Ethiopia response to El Niño inversely, unlike La Niña (Korecha and Barnston 2007). However, the small rainy season in Ethiopia boosts during El Niño (Wolde-Georgis, Aweke et al. 2010). South African summer rainfall and Niño3 index are linked in an opposite way. However, the spatial linkage of late summer rainfall is greater than early rainfall (Kruger 1999).

In eastern Africa El Niño (La Niña) tends to bring above (below)-normal rainfall (Camberlin, Janicot et al. 2001). In Kenya, wetter (drier) conditions compared with normal years observed during warm (cold) phase (Karanja, Mutua et al. 2000). Amissah-Arthur, Jagtap et al. (2002) find that during El Niño years, rainfall on average is 72mm more than normal years and is 103mm greater during October-January in Kenya. Generally, during El Niño years, eastern Africa receives grater rainfall in October to March than normal years, that secondary crop season benefits from. Though, equatorial eastern regions (Kenya, Uganda, the United Republic of Tanzania, southern Somalia and southern Ethiopia) tend to have a great probability to suffer from floods (FAO 2014). El Niño events in northeastern region of southern Africa, including of northern Malawi, eastern Zambia, northern Mozambique, and Tanzania cause increase in October-December rainfall (USAID 2014).

2.2.4 Europe

The core mechanism of the European climate anomaly and ENSO linkage is not obvious (Ineson and Scaife 2009). ENSO impacts on Europe arise from an intermediate step between the tropical Pacific. The North Atlantic Oscillation plays a dominant role in shaping European weather and climate anomalies (Merkel and Latif 2002). 40 percent of the North Atlantic Oscillation variation can be explained by ENSO (Raible, Luksch et al. 2004). El Niño events in late winter tend to co-occur with negative North Atlantic Oscillation index, downward temperature and rainfall anomalies in Europe (Brönnimann, Xoplaki et al. 2007). El Niño-related weakening North Atlantic Oscillation response over Europe is consistent and making central Europe and the western Mediterranean wetter, and Scandinavia colder (Hurrell and Van Loon 1997, Merkel and Latif 2002).

Studying European climate during the past 500 years, Brönnimann, Xoplaki et al. (2007) confirm a stationary connection between ENSO and late winter during the past 300 years. In twentieth century, during El Niño late winter temperature anomaly in northeastern Europe is negative. Turkey presents positive temperature anomaly. Negative and positive rainfall anomalies happen in around 45°N and in Norway and the southeastern Mediterranean region, respectively. Early winter, late winter and spring show different seasonal anomalies respect to ENSO, but the El Niño and La Niña effects are about symmetric. Later, Ineson and Scaife (2009) present evidence for El Niño cold and mild conditions of late winters, respectively, in northern and southern Europe. Europe tends to confront a relevant increase (decrease) of wintertime rainfalls under warm (cold) ENSO events, while the impact of ENSO appears to be more coherent in western Europe (Zanchettin, Franks et al. 2008). Winter rainfall increase during El Niño covers a wide belt from Central Europe to eastward across the Eurasian continent (Ineson and Scaife 2009). ENSO impact on Euro-Mediterranean rainfall has been stable since the last half of the 20th century. This effect is seasonally varying and not as large as tropical anomalies, but it would be considerable for such a light rainfall receiving area. The early start to the rainfall season in western Mediterranean, during El Niño, causes a 10 percent rise in the autumn rainfall prior to the ENSO mature phase. The same amount reduction appears in the spring after a mature phase, due to earlier decay. ENSO-induced Euro-Mediterranean rainfall variability is significant during winter and spring in central and eastern Europe, as well as, during autumn and spring in western Europe and the Mediterranean region (Mariotti, Zeng et al. 2002). Southern Mediterranean and northern Europe, during El Niño, face a rainfall decrease (Ineson and Scaife 2009). Southern Europe, during summer and autumn, encounter increased rainfall in a predominant El Niño condition (Mariotti, Zeng et al. 2002, Park 2004), whereas, converse anomalies develop during spring (Shaman and Tziperman 2011). Positive anomalies of wintertime precipitation over Germany, Britain and France found by Zanchettin, Franks et al. (2008), also negative anomalies over Scandinavia by Zhang, Zhu et al. (2008) and Fraedrich (1994).

Shaman (2014) finds that the European rainfall receives the largest ENSO impact in boreal autumn (October-December). The observational rainfall analysis represents positive anomalies over Iberia, western and southern France, northern Italy, the British Isles, and southern Scandinavia. ENSO variability is connected to a dipole along the coast of Europe in spring (April-June).This causes a statistically significant rainfall increase over France and Britain. The negative rainfall anomalies during summer (July-September) over northern Europe are marginally connected to El Niño events. Pozo-Vázquez, Esteban-Parra et al. (2001) analyse the ENSO-associated winter temperature in Europe during 1973-1995. The winter temperature difference between La Niña and normal years is statistically significant, but not regionally the same. There is a negative correlation for center and south of the Iberian Peninsula regions and positive for northern Britain and southern Scandinavia. The difference between El Niño and normal winter temperature is insignificant.

2.2.5 Australia

Rainfall in Australia is largely dependent on ENSO and major droughts are associated with ENSO events (Nicholls 1991, Chiew, Piechota et al. 1998). Australian rainfall during El Niño is significantly less than average rate, especially in northeastern and southeastern regions (Taschetto and England 2009, Cai, Van Rensch et al. 2011). More than 60 percent of Australia, mostly the eastern, experience drought during September–November (austral spring season) (Wang and Hendon 2007). La Niña events, versus El Niño, are parallel with rainfall amplification and air temperature reduction.Verdon, Wyatt et al. (2004) show that 50-100 percent rainfall enhanced during the cold phase into a warm phase in eastern Australia.

2.3 The effect of ENSO on cereal production

ENSO events are associated with weather patterns and, by corollary, can alter the crop production around the world. The ENSO effect on crops yield was established already in the 1980s (Handler 1984, Nicholls 1985). The strongest ENSO impacts on spring and summer crops during the boreal winter result in the most directly influence on spring–summer field crops in the southern hemisphere (Royce, Fraisse et al. 2011). ENSO event is generally related to drought in the Indian monsoon which results in low grain yield over South Asia and Australia and high grain yields over North America (Garnett and Khandekar 1992). Generally, crop yield in the western Pacific countries, during La Niña, tends to be more than normal, unlike in the eastern Pacific countries (Liu, Yang et al. 2014).

2.3.1 Wheat

Shuai, Zhang et al. (2013) investigate the effect of ENSO on the main crops including wheat, during the decaying stage of ENSO years, in China. Wheat, exclusively, faces large area of yield reduction during El Niño phase that is notable in northern and southeastern (mainly due to the increased precipitation) China. A few provinces benefit from El Niño. La Niña years are more favourable for wheat yield, compared to El Niño years, especially, in southern and southeastern China. Although, in some provinces mostly in northeast and southwest slight drop in wheat yield is evident. In La Niña years in most provinces, there are opposite responses, apparently due to the almost contrary climate variation from El Niño years. Bannayan, Lotfabadi et al. (2011) find a positive significant correlation between Niño3.4 (in July, August and December) and wheat yield in a northeastern province in Iran. Garnett and Khandekar (1992) and Khandekar (1996) investigate the ENSO effect on Indian monsoon and on cereal production and worldwide grain yields, focusing on the different areas of South Asia, Australia and the North American prairies. They result that ENSO is associated with low grain yield in Australia and South Asia, unlike the North American prairies.

Wheat in the southeast U.S. typically benefits from increased winter precipitation during El Niño. There is a tendency for higher yields during El Niño years, but with little difference between the normal and El Niño years. Wheat shows a significant response to existing and following ENSO phase. Wheat yields are lower following very strong El Niño compared to following other El Niño events. Yield is high following La Niña and low following El Niño events (Hansen, Jones et al. 2001). Woli, Ortiz et al. (2015) examine ENSO effect on early and late maturity group of winter wheat in the southeastern U.S. Results show that ENSO impacts winter wheat depends on region and cultivars. During El Niño phase late maturity groups tend to have higher yield than early cultivars in northern region. During La Niña phase, early cultivars yield is more than late cultivars in southern part. In Mexico, there is a net rise in wheat and maize area planted, during La Niña years. The area of wheat planted increases about 8.6 percent but, not significant changes in El Niño years. Whereas, the percentage reduction in maize area planted is 5.9. In general, winter wheat yield response to El Niño and La Niña phases is negative and positive, respectively (Adams, Houston et al. 2003). Pol and Binyamin (2014) find that extremely wet (drought) summer of El Niño (La Niña) years both result in reduction in wheat and maize production in Argentina.

Gimeno, Ribera et al. (2002) evaluate the ENSO and NAO effect on main crops including fruits and cereals in Spain. ENSO influence on mean yield is more likely on fruits than cereals. The variance of the three ENSO phases is not high for cereals including wheat. Wheat yield tends to be low during La Niña years than El Niño years.

Rimmington and Nicholls (1993) find wheat yield in Australia is correlated with the SOI of the year before planting and concurrent SOI with crop season in a negative and positive manner, respectively. Meinke and Stone (1997) evaluate the effect of SOI phase on wheat production in Australia and Brazil. Negative SOI has negative significant effect on yield in Australia and positive effect in Brazil. Positive index is correlated negatively, but is only significant in Brazil.

2.3.2 Maize

Handler (1990) demonstrates the relationship between ENSO-induced SST anomalies in the equatorial Pacific Ocean and maize yields deviation from long term trends throughout the continental U.S. He finds negative correlation with SSTAs for winter prior to growing season in southeast northward to the Great Lakes. On the other hand, positive correlation with SSTAs for following autumn in Florida and the Upper Midwest corn belt. Hansen, Hodges et al. (1998) study the ENSO impact on multiple crops including maize in the southeastern U.S. in a 35 years period. They suggest that ENSO events have significant impact on maize yield and value. Maize yield increases in La Niña years and decreases in the subsequent years. ENSO phases explained an average shift of US$212 million of the value of maize. He concludes 26 percent, on average, of the maize value variations determined by ENSO. In the U.S. Corn Belt about 15 percent of crop yield variation can be attached to Pacific sea-surface temperatures (Phillips, Rajagopalan et al. 1999, Wannebo and Rosenzweig 2003). Phillips, Rajagopalan et al. (1999) also, examine the ENSO impacts on maize yield variation in the U.S. Corn Belt. Their analysis suggests yield decline during La Niña episodes and yield increase during El Niño phase. However, the yield decrease is greater than the average level of improvement. The cause of the yield loss is undesirable condition of the heat stress due to temperature rise and rainfall cut in La Niña phase (Todey, Carlson et al. 1999). Legler, Bryant et al. (1999) investigate the role of ENSO in seven crops (barley, maize, soybean, sorghum and cotton and winter/spring wheat) in the U.S. and find a negative effect on all crops except winter wheat in El Niño years and maize in La Niña years. They also report that northern areas are more impressible by El Niño and southern areas are similarly impressible during La Niña. Podestá, Messina et al. (1999) investigate ENSO effect on several crops including maize in Argentina. Maize yield tends to be higher (lower) during warm (cold) ENSO events. In addition, the yield decline during La Niña events is, on average, greater and more consistent than yield rise during El Niño events. Martinez, Baigorria et al. (2009) investigate the connection between some climate anomalies (including ENSO) and maize yield in the several states of the U.S. They find a negative link between ENSO and local weather and yield. It indicates El Niño–associated cooler and wetter winter and spring corollary is related to yield reduction. Podesta, Letson et al. (2002) review maize, soybean and sorghum yield variations in the ENSO cold and warm phases in the region of central-eastern Argentina. Positive (negative) effect on national-level yield of these crops observed during warm (cold) ENSO phase. Among all, maize represents the closest relation. Later, Travasso, Magrin et al. (2003), using data 1950–94, investigate the correlation of maize yield in Buenos Aires province and equatorial SSTA, as well as South Atlantic SSTA. Results show the one direction association between equatorial SSTA and maize yield. Pol and Binyamin (2014) declare soggy fields during El Niño and droughts during La Niña in Buenos Aires summer result in wheat and maize production reduction. In the state of Rio Grande do Sul in Brazil, there is a strong tendency for El Niño to provide opportunities to favour maize crops, while for La Niña years there is a high frequency of downward yields (Berlato, Farenzena et al. 2005).

Tao, Yokozawa et al. (2004) analyse the variability of staple crops (maize, wheat and rice) in the major agricultural regions of China regarding ENSO event. Among reviewed crops, maize production has been more vulnerable to strong ENSO. In such a way that maize yield on a national scale decreases about 5 percent in El Niño phase, compared with normal years. This reduction in one of the Central provinces is estimated at about 16 percent. Liu, Yang et al. (2014) investigate the ENSO-induced variation on winter wheat and summer maize in the North China Plain. In this study, agricultural production systems simulator model and data of daily temperature, precipitation, and sunshine hours during 1956-2006 has been applied. Results state that, in both warm and cold ENSO phases, crops yield is less than normal years for rainfall reduction, lower sunshine hours and absence of additional irrigation. In addition, maize is most influenced than wheat. Shuai, Zhang et al. (2015) conclude maize yield, during El Niño years, increases in most of China, especially northern China. A part of southern regions experience yield decrease. During La Niña years, an apparent yield reduction happens in the north and northeast regions and a general elevation in the southern regions. ENSO-induced rainfall variability in northern and northeastern China during growing season is more responsible for maize yield variability, compared to temperature and solar radiation. In Indonesia, ENSO events influence the timing of maize production, but apparently not the level of production (Naylor, Falcon et al. 2002). Maize planting delay at onset of an El Niño year rainy season makes up by a later greater planting in the year. As a result, there are nearly no significant associations between annual maize production and ENSO.

Phillips, Cane et al. (1998) find maize yield in Zimbabwe is highly correlated with simultaneous SSTA in the Niño3 region during growing season. Surprisingly the correlation of Niño3 index and maize yield is stronger than with rainfall (Cane, Eshel et al. 1994). In addition, they show the correlation with observe Niño3 index for about one year in advance of growing season. 57 percent of the yields variability refers to SST of a year earlier planting (Cane, Eshel et al. 1994). Du Toit and Prinsloo (2001) observe that El Niño events impact on South African national maize yield vary from 2100 kg ha−1 (near average) to 875 kg ha−1. Milder episodes were correlated with greater national level yields toward the stronger or super events.

2.3.3 Rice

Intensive droughts associated with the two last considerable El Niño events have led to a delay in harvesting rice in Indonesia which were followed by severe problems of food supply for poor households (Harger 1995, Amien, Rejekiningrum et al. 1996). Naylor, Falcon et al. (2001) quantify the connection between ENSO indices and rice production in Indonesia (Java) and observed fluctuations in rice plantings and production. Naylor, Falcon et al. (2001), Naylor, Falcon et al. (2002) and Falcon, Naylor et al. (2004) in their investigations in Indonesia find that the area harvested is more affected than yield. Naylor, Falcon et al. (2002) find that year-to-year August SSTA variations specify almost 50 percent of interannual paddy production variability during the wet season. Every 1˚C change in August SSTAs, result in 1.4 million tonnes fluctuation in Indonesia’s paddy production, on average. In northern China, the outbreak of the oriental migratory locust which is a pest of rice and feeds on leaves at all growth periods, tend to infest one or two years after El Niño event (Zhang, Sumi et al. 1999). Changes in precipitation and air temperature are apparently the reason of this occurrence. Tao, Yokozawa et al. (2004) suggest that ENSO event does not greatly influence on rice production in China. While Zhang, Zhu et al. (2008) find rice yield associated with rainfall and temperature varies from ENSO and normal years in China. Tao, Hayashi et al. (2008) and Zhang, Zhu et al. (2008) evaluate the ENSO event association with rice yield in north and northwest of China. They find an inconsistent linkage in most provinces at different terms of 1960-2004. Before 1980, rice vulnerability can be traced to El Niño events; but not afterward. Water supply development in these regions was the main reason for the inconsistency. More recently, Deng, Huang et al. (2010) find that Jiangxi is the most affected region by ENSO in China. Whilst ENSO is well associated with rainfall, early, middle or late rice yield are not significantly correlated with ENSO. Shuai, Zhang et al. (2013) show that rice yield in northeastern China increases during El Niño event due to the higher temperature. In contrast, it reduces in central regions due to the higher rainfall. Various authors have demonstrated that El Niño leads to a postponement of the rice planting in the Philippines (Dawe, Moya et al. 2009, Roberts, Dawe et al. 2009). Lansigan (2005); Lansigan, De los Santos et al. (2000) examine ENSO effect on rice production in different ecosystems in the Philippines and find negative El Niño impact on rainfed rice production. Roberts, Dawe et al. (2009) investigate the ENSO impact on rice yield and production in various ecosystems and seasons in the Philippines (Luzon) during 1970-2005. They conclude that El Niño has a significant effect on both ecosystems and it is greater in a rainfed system. Production during the dry season is more affected in El Niño years with a large decrease. The effect on the area harvested is more than yield in the both ecosystems. Zubair (2002) finds Maha (October to March) rice production in Sri Lanka increases during El Niño phase while Yala (April to September) production decreases, whereas opposite results are observed during La Niño events. Jintrawet and Buddhaboon (2011) investigate the impact of ENSO on rice production in the time period of 1980-2002 in Thailand. Despite the negative impact on rainfall, the ENSO phase did not affect rice yield and the planted area because of the sufficient rainfall during main growing season. Selvaraju (2003) examines ENSO linkage and production of cereals and legumes in India and finds relatively greater impact on rice than others. During El

Niño and La Niña events rice production decrease by 7 percent and increase by 3 percent in India, respectively.

Roel and Baethgen (2007) evaluate the impact on (October-December) SSTA in Niño3.4 region, in period of 1972-2003, on rice production in Uruguay. The results reveal that it is more likely to obtain more yields in the cold phase, regarding normal condition. El Niño events cause rice yield reduction in Uruguay.

2.3.4 The effect of ENSO on global cereal production

Chen and McCarl (2000) apply stochastic model with global trade model to study ENSO effect on wheat, maize, soybean and sorghum in the main crop producing countries. Their result show that maize and sorghum productions negatively impact in the both ENSO phases. In this regard, different wheat varieties response differently during El Niño events, but there is a positive shift in all wheat cultivars production during La Niña event. Chen, McCarl et al. (2008) examine the effect of the average and strong (1997/1998 El Niño) ENSO on the main rice exporters and importers in the world. Their results indicate that during El Niño phase rice production decreases in China, Myanmar, Vietnam, and the U.S., Australia, North Korea, the Philippines, Central America and Europe range from 0.2 percent to 5.8 percent. Rice production during La Niña phase reduces more than El Niño phase. They also conclude that an average El Niño or La Niña event, both, make a reduction in global rice production, as well as an extreme El Niño event. Iizumi, Luo et al. (2014) globally map ENSO impact on the yield of major crops. They quantify the ENSO effect on the global-mean yield anomalies of maize, wheat, rice and soybean. Their result suggests that during both phases of ENSO the global mean yield of maize, rice and wheat are below than normal phase (up to 4 percent reduction). The global mean yield of soybean tends to increase during El Niño events, unlike La Niña.

2.3.5 Methods used to measure the impact of climate variability on agriculture

ENSO related research arouses a great deal of interest for some reasons: ENSO can be modelled, ENSO has worldwide climatic influences (Yokoyama 2002, Yokoyama 2010); ENSO predictability (Latif, Anderson et al. 1998, Fedorov, Harper et al. 2003) and a temporal lag between atmospheric and oceanic interactions and climatic consequences (Klein, Soden et al. 1999). Researches on ENSO mainly can be classified into three categories: Research on the mechanism of ENSO (e.g. Collins (2000), Schopf and Burgman (2006)), research on economic, social and ecological consequences of ENSO (e.g. Cashin, Mohaddes et al. (2015), Hicks and Maldonado (2015), Acosta-Jamett, Gutiérrez et al. (2015)) and research to inform the ENSO adaptation (e.g. Patt and Gwata (2002)).

This study contributes to the researches on the ENSO impact on global cereal production and provides a general discussion on adaptation policy. Two main types of methods have been employed to model yield/production variability relating to ENSO:

- A regression-based framework to directly estimate the ENSO impact on crop production using historical data (Roberts, Dawe et al. 2009, Deng, Huang et al. 2010, Tack and Ubilava 2013).
- Assessing the ENSO effect on crop yield/production by comparing the deviations of the "anomalous" and "normal" years, applying simulation methods (Phillips, Rajagopalan et al. 1999, Amissah-Arthur, Jagtap et al. 2002, Chen, McCarl et al. 2002).

One of the main problems using crop simulation model is the presence of “considerable uncertainty about physiological process (functional form) and the many parameters in these highly non-linear models” (Schlenker and Roberts 2008). The other problem is “the assumption of exogenous production systems and nutrient applications: there is no account for behavioural response on behalf of farmers" (Schlenker and Roberts 2008). In this study, the analysis is based on regression approach to evaluate the effect of ENSO on the cereal production in the world.

2.4 El Niño-Southern Oscillation and commodity prices

It is well documented in the existing literatures that weather anomalies affect agricultural production which may result in shortage or excess supply in some area or total of the world. In the regions where ENSO influence are strong, commodity prices variation could account for increasing or decreasing total agricultural production (Keppenne 1995, Hansen, Jones et al. 1999). These changes could potentially result in a shift in world prices of agricultural commodities. Naylor, Falcon et al. (2001) state that the absence of compensation policies to offset the rice production shortfall during strong ENSO years leads to the instability in domestic price that causes severe and negative impact on low income households. Seasonal climate predictions on the basis of ENSO indications provides farmers the opportunity of prediction and reaction to price fluctuations. Using management practices by farmers moderate the direct impact on yield, thereby the indirect effect on farm income (Hansen, Jones et al. 1999, Hill, Butler et al. 2001). Management practices influence prices through their effect on production and supply. These, in turn, have further impact on producers net returns (Hill, Butler et al. 2001).

Many studies investigate the effect of climatic anomalies on crop productions and commodity prices. The two-month delay in rainfall due to ENSO events, postponed plantings and subsequent harvest in the main rice producing regions in Indonesia when harvest is characteristically paralleled with increasing consumer prices (Mears 1981, Ellis 1993). ENSO direct impact on soybean futures price is through teleconnections in planted regions. But, the indirect influence could be through its impact on anchovy catch, since it competes with soybean that accounts for a protein source for feed (Rosenzweig and Hillel 2008). Keppenne (1995) has examined the relationship between monthly soybean futures price and ENSO behaviour, revealing close linkages with the La Niña phase of the ENSO cycle. Letson and McCullough (2001), using Granger causality tests to investigate the connection between monthly cash prices for soybean, finding an insignificant relationship. Brunner (2002) examines the ENSO effect on real non-oil primary commodity prices along with inflation and GDP growth in G7 countries. He finds an economically and statistically significant impact on real commodity prices and inflation. The analysis reveals that a single standard deviation increase in sea-surface temperature results in about 3.5-4 percent rise in real commodity price inflation.Temin (2002) provides evidence that barley and mustard prices are correlated with the variation in growing condition. Chimeli, De Souza Filho et al. (2008) assess the ENSO effect on maize production and price and find positive impact on price and negative effect on maize production. There is evidence of the linkage between sharp enhancement for palm oil price and El Niño events (Bromokusumo and Meylinah 2009). Dawe, Moya et al. (2009) find a large increase in the rice price in the Philippines, following El Niño events (1972-73, 1982-83, and 1991-92). However, this impact in 1997-98 El Niño was avoided by a policy response. Ubilava and Holt (2009) apply smooth transition vector error correction model to investigate the ENSO effect on vegetable oil prices; report evidence of increasing price during El Niño events and decreasing in La Niña events. In a related study, Ubilava (2012) finds ENSO is statistically associated with coffee price in the short run, although different varieties for geographical dispersion are affected in a different manner. In addition, Ubilava (2014) examines the effect of ENSO on wheat price dynamics of five major exporting regions including the U.S., Canada, Australia, EU, and Argentina. He finds symmetrical positive and negative response during La Niña and El Niño events, respectively.

2.5 Macroeconomic consequences of El Niño-Southern Oscillation

Aside from the evidence of rainfall and temperature variations on crop yields and prices, the study of the connection between large scale medium-frequency climatic anomalies and economic factors is noteworthy. Many studies have examined the possible correlation between SST anomalies in the central Pacific Ocean and some macroeconomic implementations (Brunner 2002, Berry and Okulicz-Kozaryn 2008).

Adams, Chen et al. (1999) estimate the economic result of the 1997-98 El Niño (the most severe one in the world) as well as following La Niña event (1998-99) on U.S. agriculture. They consider multiple crops and use stochastic economic model of the U.S. agricultural sector. They find economic loss for both phases, equivalently US$1.5-US$1.7 billion for El Niño phase and US$2.2-US$6.5 billion for La Niña. Selvaraju (2003) analyse the ENSO impact on the economy of India and estimate US$773 million loss during El Niño phase and US$437 million advantage in La Niña event. Chen, McCarl et al. (2008) investigate the impact of medium and severe ENSO event on rice production in 23 Indica rice production regions. They report annual welfare compensation of more than US$2800 million due to reduced production and trade fluctuations in medium ENSO years. In this respect, an extra US$500 to US$600 million welfare loss for extreme ENSO events has been estimated.

2.6 Economic value of ENSO Forecasts

Nowadays, predicting ENSO is a key variable in food security (Mjelde, Hill et al. 1998, Broad and Agrawala 2000). Pfaff, Broad et al. (1999) recognise ENSO forecasting as a significant factor for food security estimation, especially in the Pacific Ocean rim countries. There is a lag of 1 to 12 months in climate variation due to the interaction of sea surface temperature with atmospheric pressure in the equatorial Pacific (Montroy, Richman et al. 1998) and this is a basis for ENSO forecasting (Chen, McCarl et al. 2002).

Because of the recent advances in knowledge of monitoring the interaction between equatorial sea temperatures and the atmosphere, ENSO prediction is now possible at lead time of several months to a year (Latif, Anderson et al. 1998, Mason, Goddard et al. 1999). It can prepare weather data to inform crop management decision making to mitigate potential adverse impacts. This can be applied to improve agricultural management and food security (Zubair 2002). Solow, Adams et al. (1998) investigate the economic value of the U.S. agricultural sector based on the accuracy of ENSO forecast using simulation methods. They estimate the annual expected value of a perfect prediction to be US$323 million. Furthermore, modest and high quality predictions contribute US$240 and US$266 million, respectively. Messina, Hansen et al. (1999) analyse the economic benefits from the skill of land allocation between cereals and oilseeds in Argentina, provided the ENSO prediction. They find that land allocation variation among crops to ENSO results in an increase in mean farm income up to 20 percent. However, the range of income increase depends on location, farmers' initial wealth and risk aversion. Jones, Hansen et al. (2000) examine the expected value of a substitution of soybean, maize, peanut, cotton and wheat response to ENSO in Argentina and the southeast U.S. They calculate the value of ENSO forecast in the Coastal Plain of the state of Georgia in the U.S. and Pampas region in Argentina. They estimate the value of optimal crop management applying ENSO forecast in the southeast U.S. from US$3 to US$6 per hectare. This value in Argentina due to the stronger impact of ENSO during the time of growing summer crops is greater from US$11 to US$35 per hectare. Later, Hansen, Jones et al. (2001) estimate mean value of optimal apply of ENSO phase information in the southeast U.S. for wheat and maize at US$4.41 and U$7.00 per hectare in a year. Chen, McCarl et al. (2002) find the value of ENSO forecast to agriculture in major crop producing countries using multi-commodity, multi-country aggregate modelling. Their results indicate that welfare has doubled by using more detailed ENSO definition in terms of forecasting. Adams, Houston et al. (2003) evaluate the economic outcome of ENSO–based forecasts in Mexican agriculture and estimate the annual economic benefit of an early ENSO warning by US$10 million.

Chapter 3. Research Design

The objective of this study is to determine the economic impact of ENSO on world grain production by quantifying the relationship between agricultural production and climatic and economic variables. The main null hypothesis is that ENSO has no impact on world cereal production, beyond its possible links with rainfall and temperature. This hypothesis will be tested against an alternative that there is the connection between grain production and the Niño3.4 Index, after precipitation, air temperature and expected prices are controlled for. The limitations of this study are: (i) the levels of applied fertilizer and chemicals are not incorporated in the analysis; (ii) pests, which tend to be affected by temperature and precipitation variation are not considered; (iii) instead of local prices (due to their unavailability in all considered countries) international prices are used, with the assumption that local and global prices are highly correlated.

3.1 Research Design Outline

This study applies an economic assessment framework to identify the extent to which the ENSO event synchronizes the global cereal production. This model is used to elucidate the crop-production effects of ENSO into changes in area harvested, price, air temperature and precipitation. The research design in Figure 3.1 shows how the study is integrated.

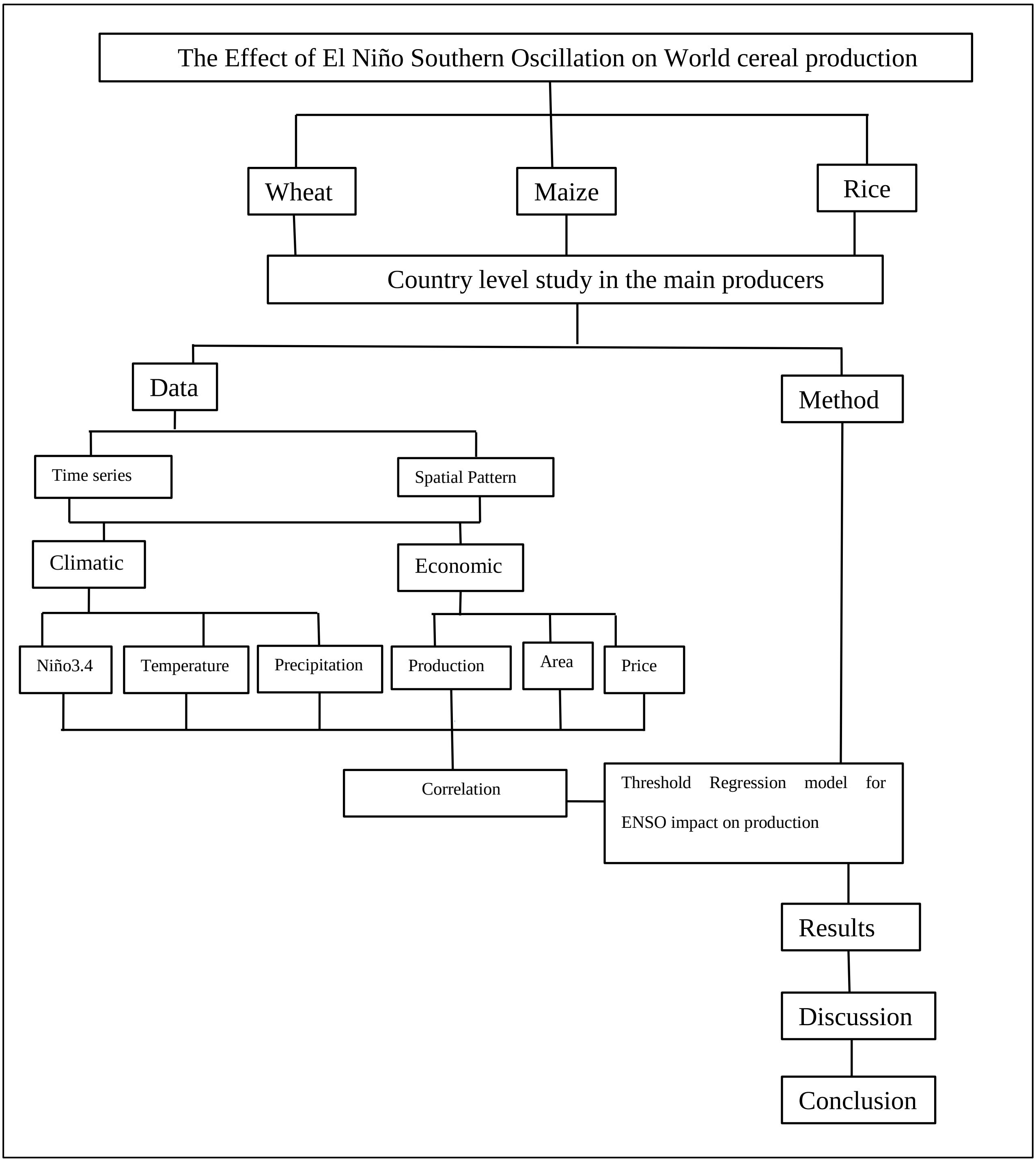

Figure 3.1. Research design flow diagram

3.2 Data and research concept

This research combines the time series of climatic, agronomic and economic data, spanning the years 1962-2009. Climatic data include monthly time series of sea-surface temperature anomaly, air temperature and precipitation. The air temperature and precipitation data are the same as in Villoria (2015). The author constructs the mean temperature and precipitation over the months covering the growing season of particular crops in a given country. The ENSO signal is defined by the sea-surface temperature anomalies (SSTA) observed in the Niño3.4 region of the central Pacific. The monthly time series of SSTAs that is derived from the NOAA Extended Reconstructed Sea Surface Temperature V3B (ERSST.V3B) is tabulated by the National Weather Service Climate Prediction Centre at National Oceanic and Atmospheric Administration (NOAA)[2]. This study uses the monthly means of SSTA values (measured in ℃) over the growing season of an individual crop in a specified country, to allow for El Niño and La Niña impact production through vectors beyond temperature and precipitation (Tack and Ubilava 2013). For a given year, the mean value of SSTA in Niño3.4 region was used to define whether El Niño or La Niña phases were present in the period of the growing season of each crop. Although~~,~~ the timing of the growth period varies by country and crop type, two different regimes are defined as below:

La Niña if $\overline{SSTA} < -0.5℃$;

El Niño if $\overline{SSTA} \geq +0.5℃$

The above definition implies that any average values that exceed +0.5 (-0.5) denotes a growing season which was impacted by El Niño (La Niña).

Country-level production and area harvested for wheat, maize and rice (paddy) are collected from FAOSTAT, which were tabulated by the Food and Agriculture Organization of the

---

[2] Available at: ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/ersst3b.nino.mth.81-10.ascii

United Nations[3.] In this study the measurement unit for crops production is tonne and for area harvested is hectare. Monthly time series prices were obtained from the historical data at World Bank Commodity Price Data (The Pink Sheet)[4]. All prices are in nominal US dollars per tonne. The international price for rice is for the 5% broken white milled Thailand rice. It is based on weekly surveys of export transactions, government standard and Free on Board (f.o.b.) Bangkok. Maize price defined for U.S. yellow maize, no.2, f.o.b. U.S. Gulf ports. Wheat price is based on the hard red winter U.S. wheat, no.1, and ordinary protein also is an export price delivered at the U.S. Gulf port for prompt or 30 days shipment. All prices are deflated by using the monthly Producer Price Index for all commodities [PPIACO] that obtained from Economic Research Federal Reserve Bank of St. Louis[5]. This research applies the real price for one month prior to the onset of the growing season that is converted to the natural logarithms form.

3.3 Main Producers

According to FAO statistics, there are 125 wheat-growing countries in the world. The number of countries producing maize and rice in the world are 169 and 124, respectively. The major producers of wheat, maize and rice are defined as the 50 countries with the highest mean production in a 20-year period during 1994-2013. After removing the countries that don’t have a complete production history, 38 countries for wheat, 45 countries for maize and 48 countries for rice are included in the analysis sample. Figure 3.2 shows a spatial representation of the countries of study[6].

---

[3] Retrieved from http://faostat3.fao.org/download/Q/QC/E
[4] Retrieved from http://go.worldbank.org/4ROCCIEQ50
[5] Retrieved from: https://research.stlouisfed.org/fred2/series/PPIACO/,
[6] The full directory of the names of each country is shown in the appendix.

3.4 Crop growing season

Crop growing season is specified as the onset of planting to the end of harvesting in a way that the beginning of the harvesting season occurs in a given year. In this study, for countries where multiple cropping systems (main/secondary, winter/spring) are available, the main cropping system, or the system with the highest area harvested, was included. The onset of planting and ending of harvesting for wheat, maize and rice in the countries of study presents in Figures 3.3 to 3.8.

This study uses the following sources to define the crops growing season:

- Global Information and Early Warning System on food and agriculture (GIEWS)[7]
- Maclean, Hardy et al. (2013)
- Agricultural Market Information System (AMIS)[8]
- Major World Crop Areas and Climate Profiles (MWCAPC) (United States Department of Agriculture)[9]
- Moradi, Koocheki et al. (2014)

---

[7] Retrieved from: http://www.fao.org/giews/countrybrief/

[8] Retrieved from: http://www.amis-outlook.org/fileadmin/user_upload/amis/docs/Crop_Calendar/121206-AMIS-online-crop-calendar_REDUCED3.pdf

[9] Retrieved from: http://www.usda.gov/oce/weather/pubs/Other/MWCACP/index.htm

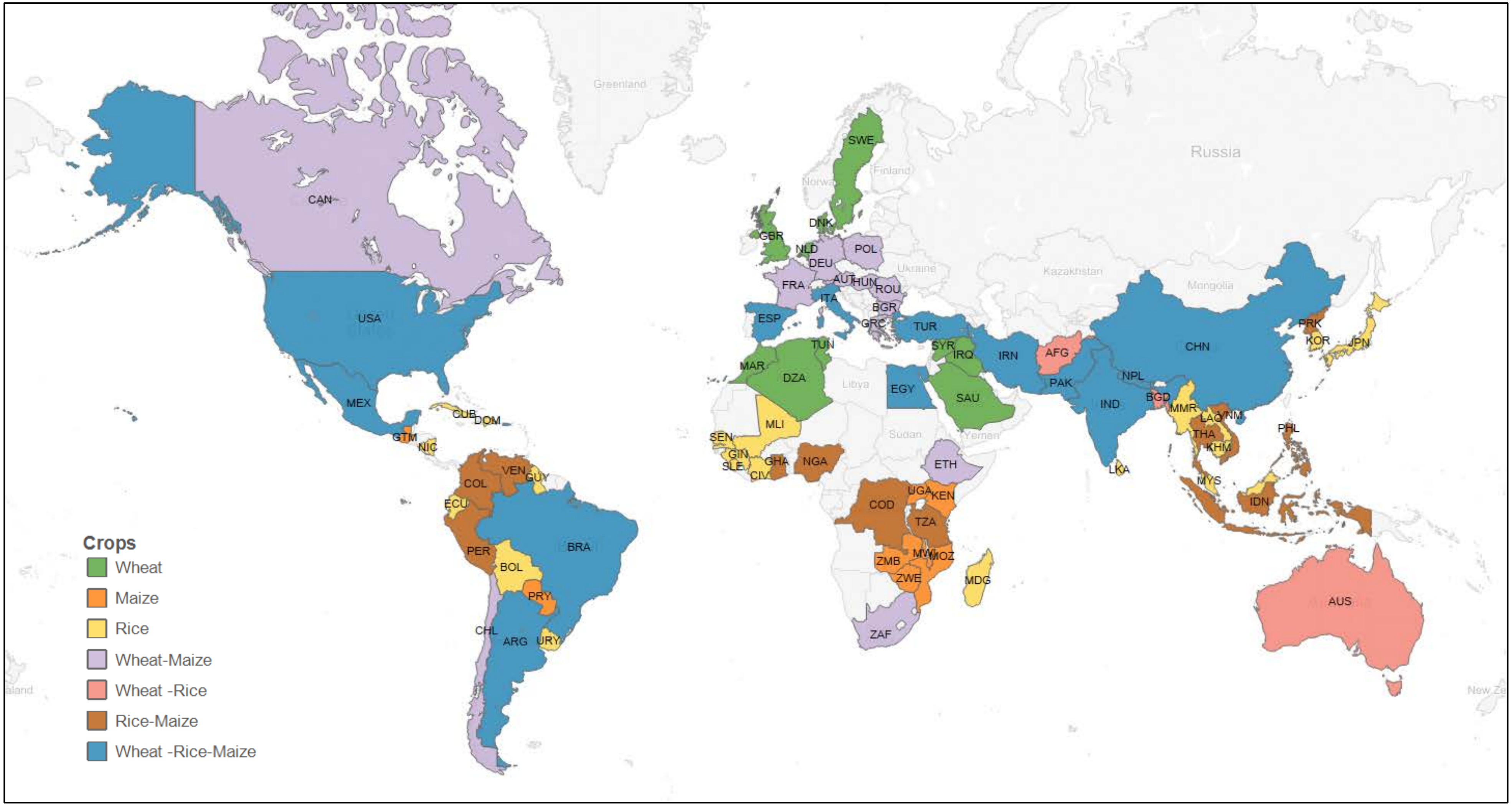

Figure 3.2. The main producers of wheat, maize and rice (countries of study).

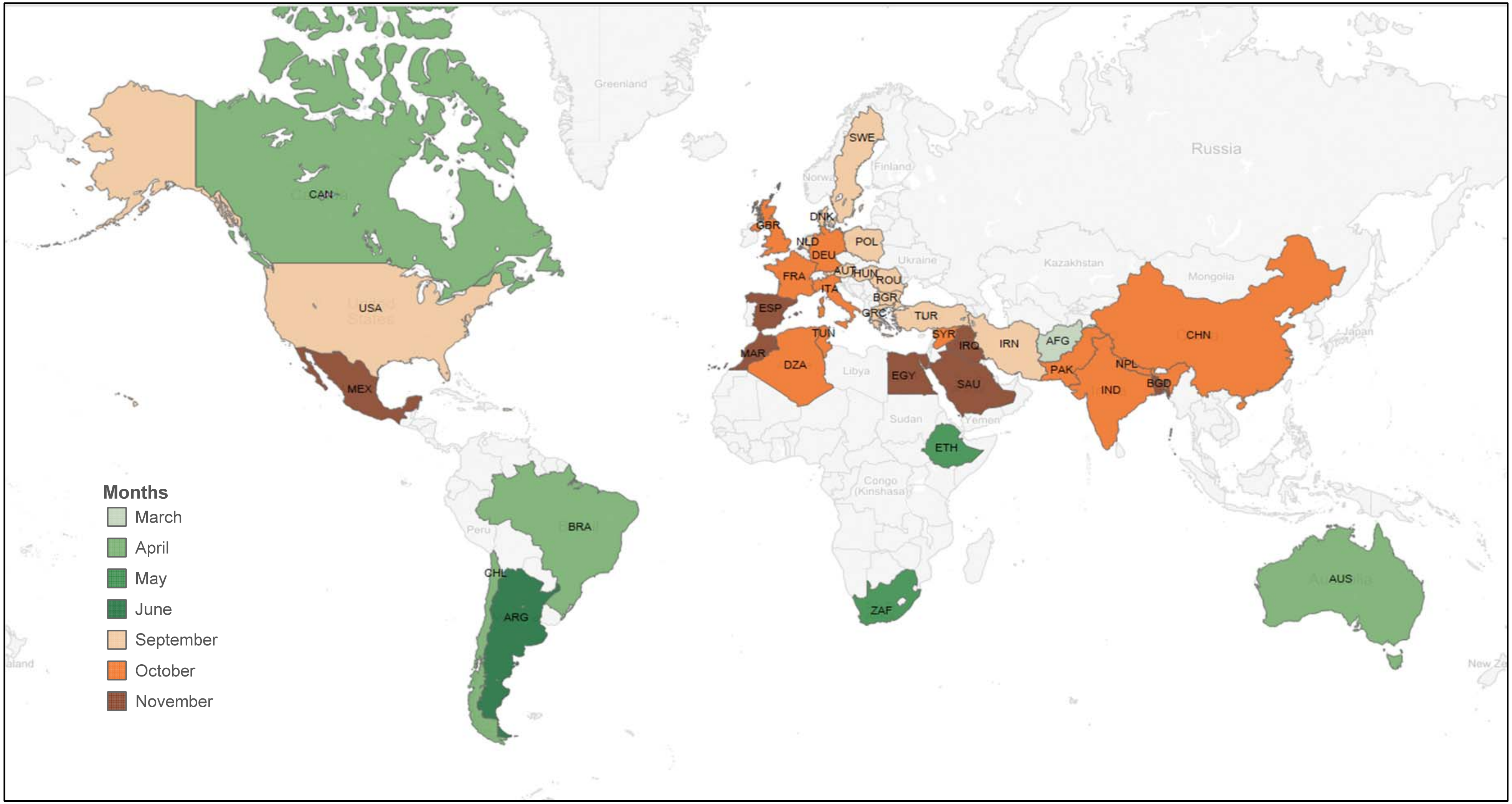

Figure 3.3. Onset of wheat growing season.

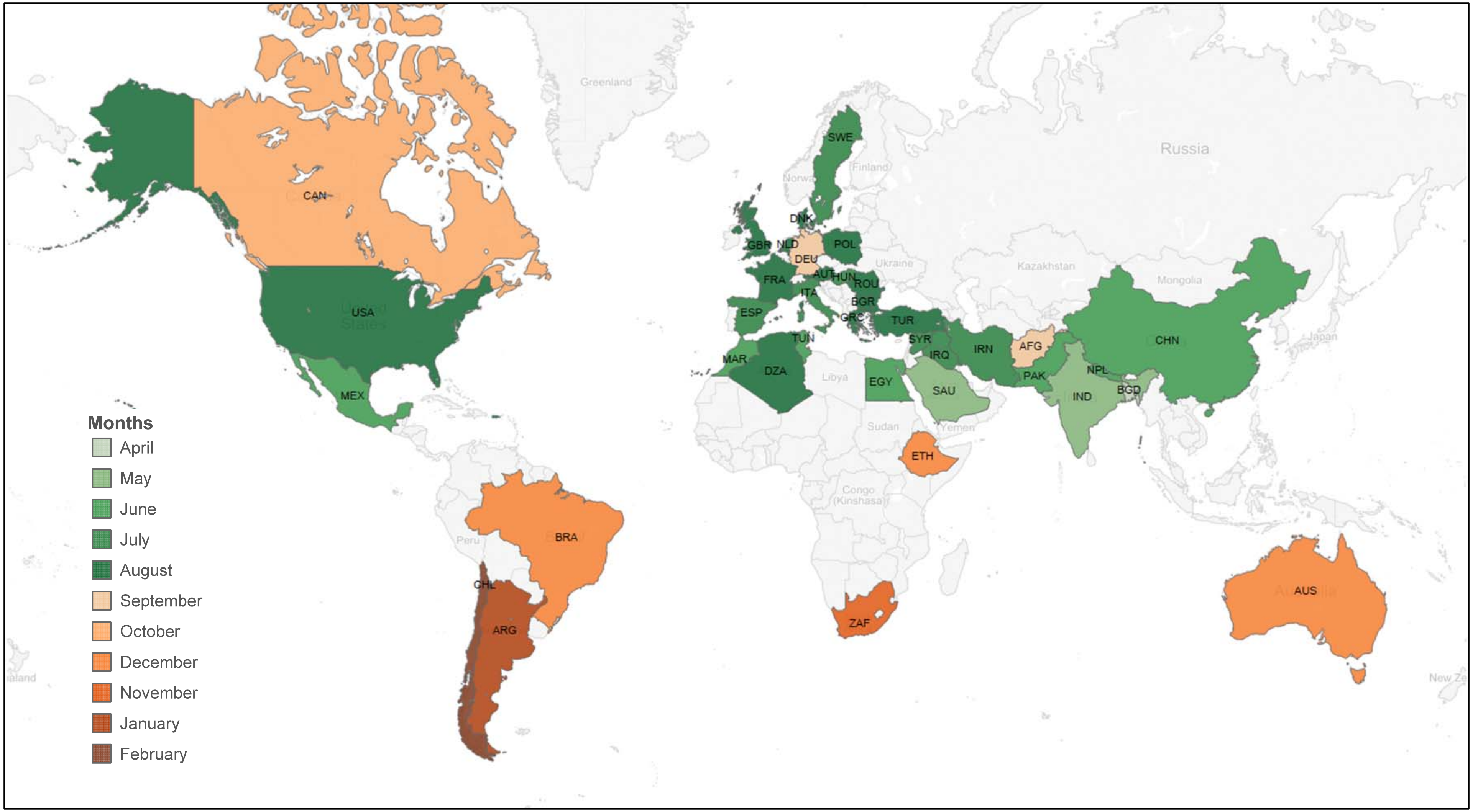

Figure 3.4. Ending of wheat growing season.

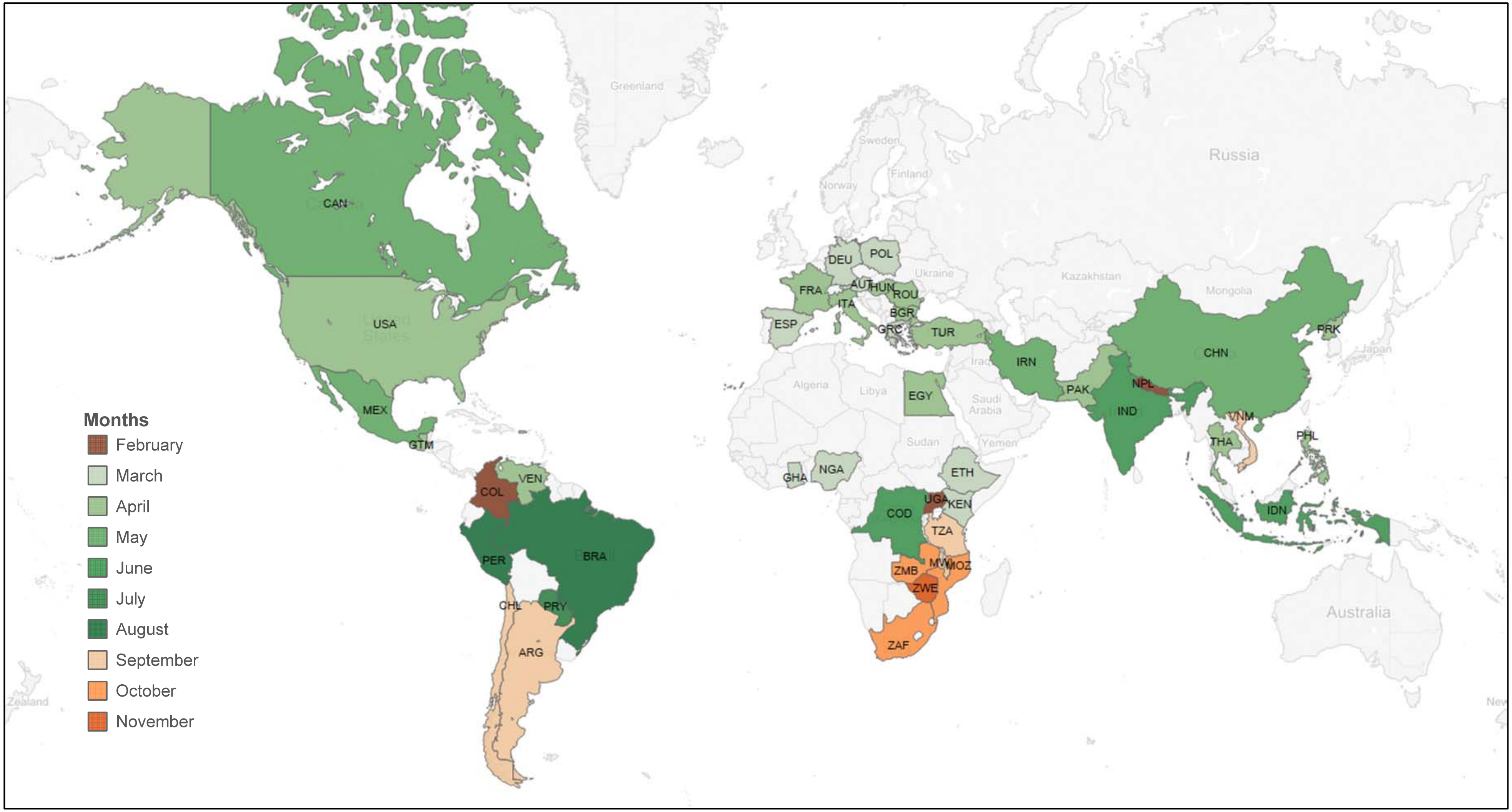

Figure 3.5. Onset of maize growing season.

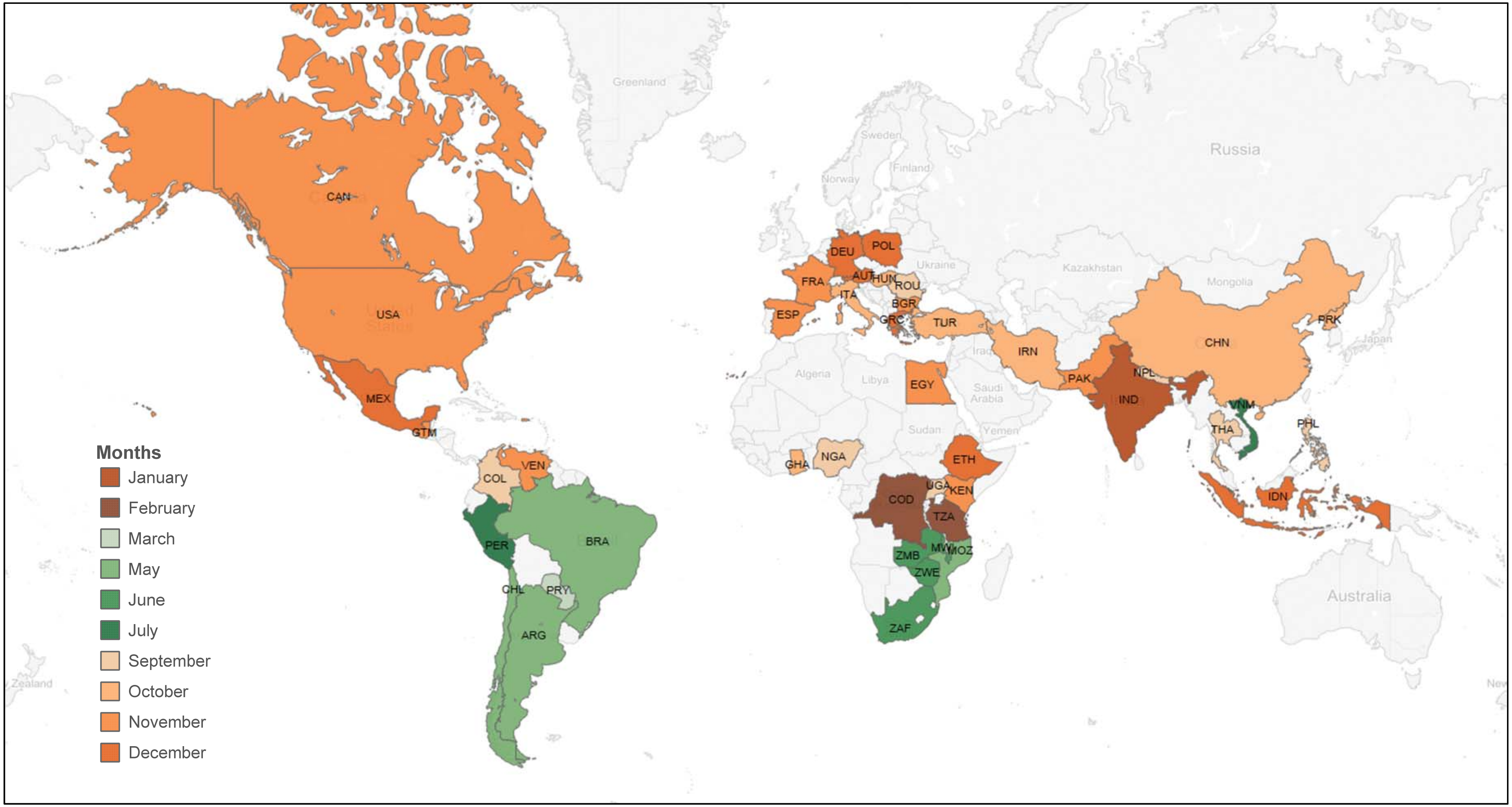

Figure 3.6. Ending of maize growing season.

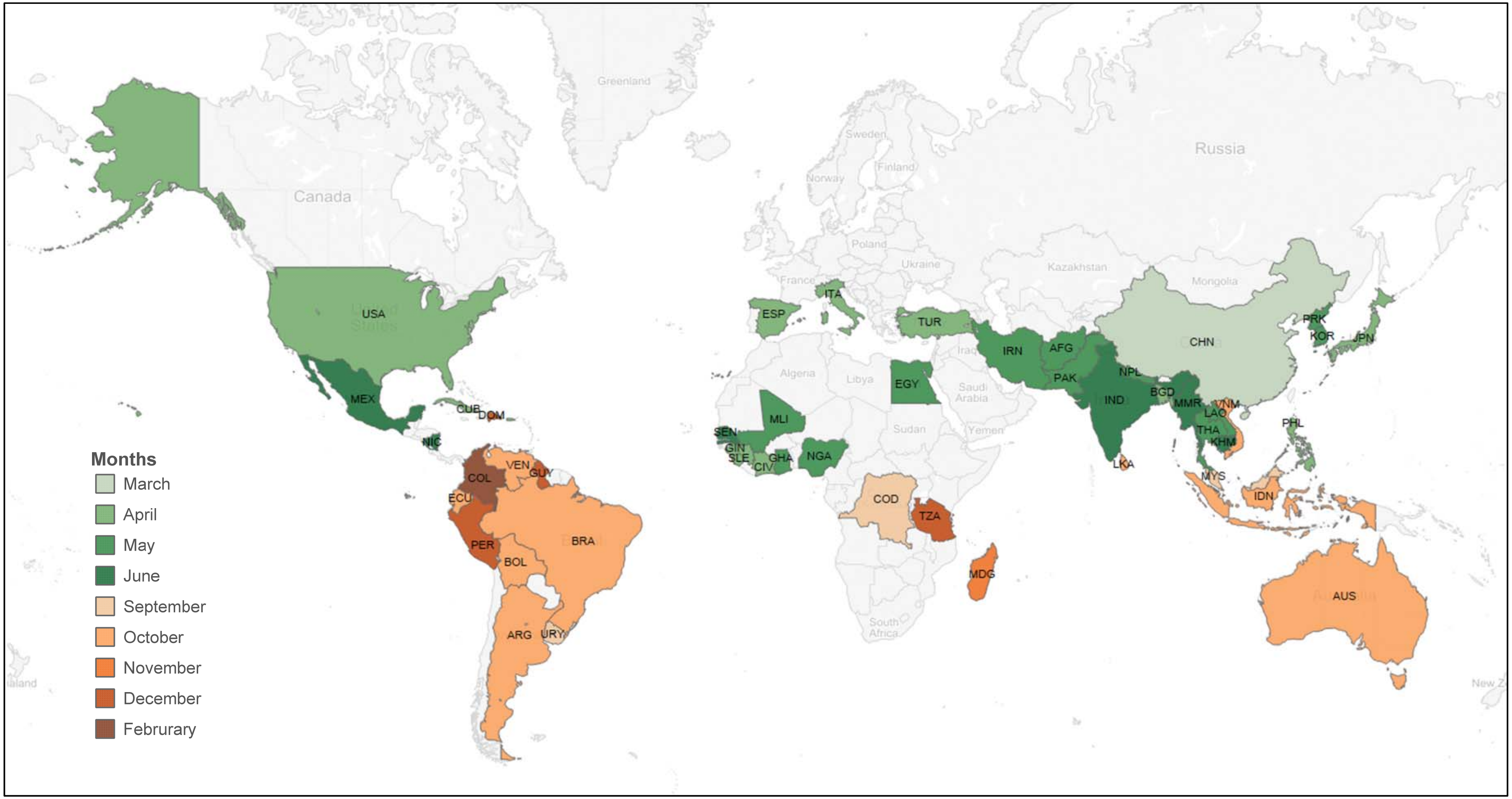

Figure 3.7. Onset of rice growing season.

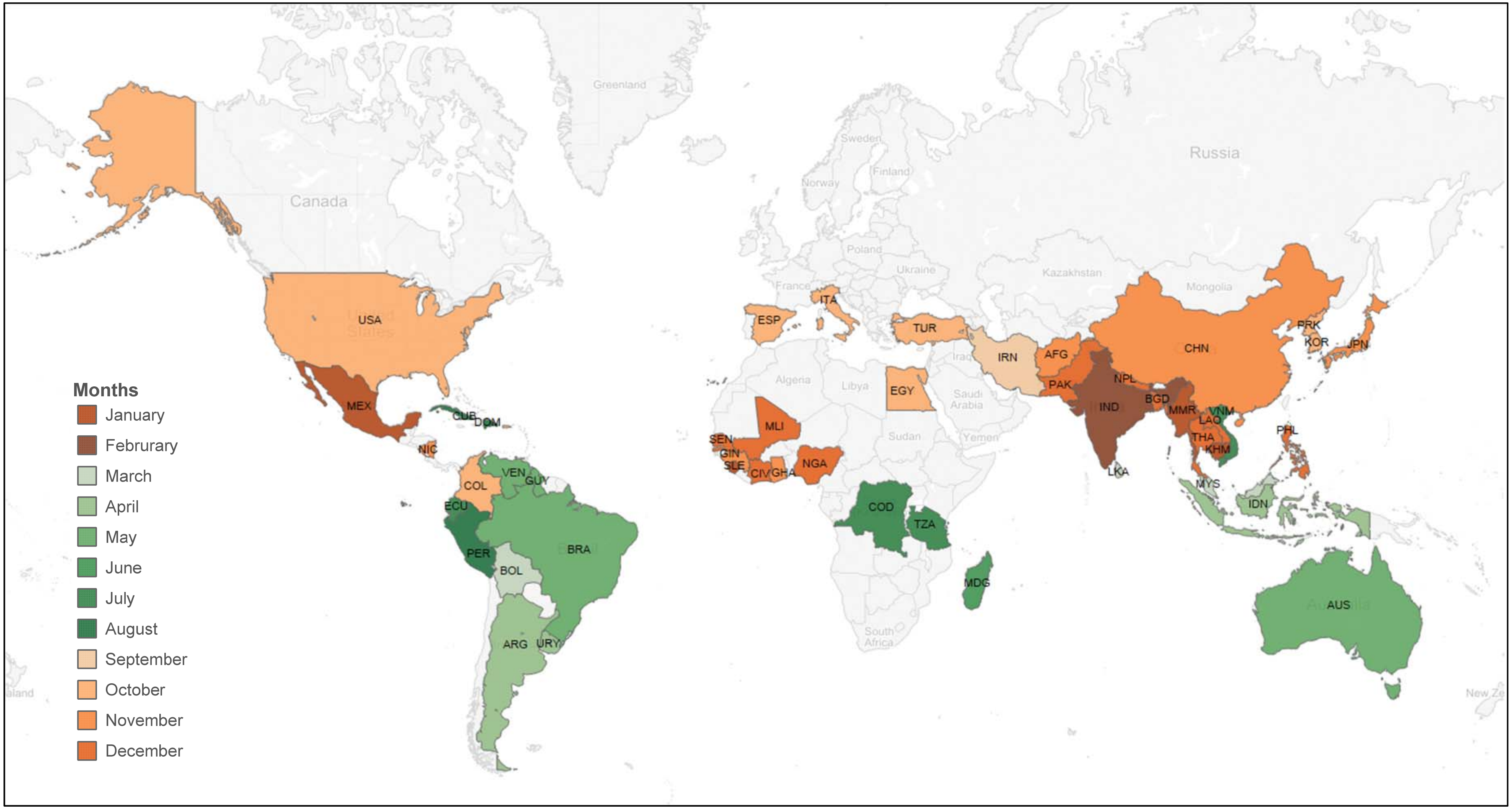

Figure 3.8. Ending of rice growing season.

Chapter 4. Methods

This study develops our understanding of climate impact by investigating the historic effect of ENSO on global grain production in a regression-based framework. The reasons that validate the use of a regression-based approach originate from the assumption that ENSO induces production variability through multiple factors (Phillips, Cane et al. 1998, Liu, Yang et al. 2014). First, ENSO-related temperature and precipitation variability (Dai and Wigley 2000, Barlow, Nigam et al. 2001) allow for a straightforward causal connection. Second, ENSO exerts extreme weather condition hazards like drought, flooding, wildfires and storms (Bove, O'Brien et al. 1998, Harrison and Meindl 2001, Mo and Schemm 2008, Harris, Nicholls et al. 2014, Ward, Jongman et al. 2014). Third, ENSO provides large changes in the development of pest and disease rates of major crops (Asian Development Bank 2009). The two recent points support incorporation of ENSO variable to control for factors that are not captured by temperature and precipitation.

The approaches of regression-based studies on climate-related production typically include one of the followings:

- Involving temperature and precipitation values as explanatory variables (Schlenker and Roberts 2009, Tack and Ubilava 2013).
- Inclusion of a dummy variable to account for climate variability (Hansen, Hodges et al. 1998, Schlenker and Roberts 2009, Deng, Huang et al. 2010, Tack and Ubilava 2013).

The current study uses the first approach and expands the second one via applying a threshold regression framework. “In threshold regression, event times are modelled by a stochastic process reaching a boundary threshold” (Lee, Whitmore et al. 2010). Similarly, the threshold values are located in the SSTA levels that define each ENSO phase. This allows for the threshold-like effect of ENSO; that is, the El Niño and La Niña shocks do not result in symmetric production responses. The asymmetric impact of El Niño and La Niña on U.S. agriculture in both aspects of size and sign has pointed out by Adams, Chen et al. (1999).

Unlike previous studies linking ENSO to crop production, the approach taken here accounts for economic factors, such as price of the considered commodity. In particular, this study incorporates the lagged (i.e., planting period) price in the regression specification as a proxy of the expected price. Price variability is frequently the leading source of production variability. Miao, Khanna et al. (2016) find a statistically significant positive price elasticity of maize yield in the United States. Expected price variability of crops could affect the farmers productive management practices and corollary crop yield (Kaufmann and Snell 1997). Following an increase in expected price applying productive management practices by farmers, (Feng and Babcock 2010) leads to an increase in yield (Miao, Khanna et al. 2016). The increase in expected price could encourage farmers to increase area planted also converting crop rotation (land switch from other crops to this crop). Alternatively, expanding the planting area to marginal, low quality fields (Feng and Babcock 2010), results in lower overall productivity (Miao, Khanna et al. 2016). By controlling for price, this study isolates the ENSO impact from the price-related production variability.

In order to isolate the effect of ENSO from weather variables, we also include temperature and precipitation variables. Also, we assume a nonlinear, quadratic relationship between precipitation and crop production, in a way that production increases almost linearly in precipitation up to a point after which additional precipitation quickly becomes unfavourable.

4.1 Econometric Framework

To assess the impact of ENSO on world cereal production, this study turns to time series data analysis. This applies because climatic variability, including quasi-cyclical fluctuation of this climate anomaly, is a function of time. Consider a baseline time series model, where crop output is expressed as a function of time:

$$y_t = \mu_t + v_t \text{ ; t = 1, 2,…, T} \quad (1)$$

Where y_t represents the natural logarithm of the crop production in a specific country at time t; and $v_t \sim \mathrm{iid}(0, \sigma_v)$ is the idiosyncratic shock. μ_t is the deterministic trend component, which controls for technological advances in agricultural production over time, and also a possible effect of global climate change, if any.

Assuming the diminishing nature of technological change, and also the likely adverse effect of climate change, the quadratic trend may be appropriate. So, the deterministic trend component can be given by:

$$\mu_t = \alpha_0 + \alpha_1 t + \alpha_2 t^2 \quad (2)$$

The linear and quadratic trend, as done by Falcon, Naylor et al. (2004) and Deng, Huang et al. (2010) sequester the ENSO impact from other time-varying factors. In other words, linear time trend accounts for increased production variability over time due to technological changes. Also, the quadratic trend reflects slow progress of technology in the last decades (Schlenker and Roberts 2008, Schlenker and Roberts 2009)

This study treats ENSO as weakly exogenous variable in the model; with the assumption that ENSO contemporaneously impacts production, but not the other way around. Moreover, in this study, ENSO variable is treated as a linear function of the sea-surface temperature anomaly as follows:

$$f(s_t) = \beta s_t \quad (3)$$

Augment the equation (1) by incorporating equation (3) results in:

$$y_t = \mu_t + f(s_t) + v_t \tag{4}$$

Where; s_t is the sea-surface temperature anomaly in the Niño3.4 region of the Pacific Ocean, and is measured in ℃. Equation (4) adopts the linear relationship between ENSO and the production variable. This assumption could be constraining because the ENSO shocks may not have symmetric effect on production, nor is it likely that the ENSO effect is a linear function of its magnitude. Put differently, two different ENSO phases, which are anomalous deviations from normal condition, can cause a distinct effect on weather conditions, and subsequently on production. Strongly emphasized anomalies are more likely to cause amplified weather conditions around the globe than small deviations from normal conditions. To account for the aforementioned nonlinearities, this study proceeds with the threshold regression (TR) analysis. The threshold regression framework, which was originally presented in an autoregressive setting by Tong (1983), augments equation (4) as follows:

$$y_t = \mu_i + \sum_{k=1}^{K}[\delta_k s_t I(\lambda_k; s_t)] + v_t \qquad \underline{\lambda} < \lambda_1 < \cdots < \lambda_k < \overline{\lambda} \tag{5}$$

Where;

δ_k, k = 1,…, K, is the parameter set associated with the ENSO variable;

λ_k represents the threshold parameter(s) defining the location of a regime change;

s_t is the transition variable, which is the ENSO variable in the current context;

$\underline{\lambda}$ and $\overline{\lambda}$ are lower and upper bounds of the threshold parameters, where the bounds are set to 15th and 85th percentile of the transition variable;

I $(\lambda_k; s_t)$ denotes an indicator function, taking values of 0 and 1, depending on s_t and λ_k ;

K indicates the total number of regimes. For example, if K=1, model (5) takes on a linear (symmetric) connection between y_i and climate. Alternatively K=2 imposes the two-regime model or a single threshold model, etc.

Here, to account for two different regimes of ENSO, El Niño and La Niña, two thresholds are introduced: $\lambda_1 = -0.5$ and $\lambda_2 = 0.5$. Moreover, we assume that the ENSO effect is insignificant during the neutral regime. This results in the following regression:

$$y_t = \mu_t + \delta_1 s_t I(s_t < -0.5) + \delta_2 s_t I(s_t \geq 0.5) + v_t \tag{6}$$

or, equivalently:

$$y_t = \begin{cases} \mu_t + \delta_1 s_t + v_t & \text{if } s_t < -0.5 \\ \mu_t + \delta_2 s_t + v_t & \text{if } s_t \geq 0.5 \end{cases} \tag{7}$$

Note that equations (6) and (7), in essence, depict three-regime models, where the parameter associated with the inner regime is restricted to zero.

4.2. Empirical model

Following the discussion above, this section outlines a regression model developed the connection of crop production to the climatic, agronomic and economic variables of interest. After incorporation the weather (i.e., temperature and precipitation), expected price, and area harvested variables in the aforementioned model, that results in the following final representation, as below:

$$y_t = \alpha_0 + \delta_1 s_t I(s_t < \text{-}0.5) + \delta_2 s_t I(s_t \geq +0.5) + \beta_1 temp_t + \beta_2 prec_t + \beta_3 prec_t^2 + \beta_4 area_t + \beta_5 price_t + \alpha_1 t + \alpha_2 t^2 + v_t \tag{8}$$

Where; y_t, $price_t$ and $area_t$ respectively represent the natural logarithm of the crop production, the natural logarithm of lagged price and the natural logarithm of crop area harvested in a given country at time *t*. The variable s_t represents the average of SSTA in the growing season of each crop in a given country to define different ENSO regimes at time *t*. The variables $temp_t$ and $prec_t$ represent the mean value of temperature and precipitation in the growing season of each crop in a given country at time t, respectively. $prec_t^2$ represents the quadratic term of precipitation at time t. The deterministic trend is applied via t and t^2 and finally $\mathrm{v_t} \sim \mathrm{iid}(0, \sigma_\mathrm{v})$.

Then, equation (8) is estimated, separately, for wheat, maize and rice in each of main producer countries. To account for statistical issues associated with heteroscedasticity and serial correlation, this research uses Newey-West procedure (Newey and West (1986)) to estimate heteroscedasticity and autocorrelation consistent (HAC) standard errors.

Chapter 5. Results

In this chapter, the method outlined in Chapter 4 is applied to the climatic and economic data sets. This study estimates country-level equations linking annual changes in the natural logarithm of wheat, maize and rice production to the changes in sea surface temperature anomalies averaged over the crop growing season. In so doing, we allow for asymmetric crop production responses to El Niño and La Niña. In addition, we control for higher frequency weather variables by adding country-level mean temperature and precipitation over growing season. Moreover, we incorporate area harvested to control for the potential yield reduction due to harvesting on a relatively inferior soil. Also trend polynomials controls for technological advances and climatic change effects. Finally, this study incorporates expected price, in the regression setting to control for the important economic variable affecting crop supply. Results reveal that ENSO impact on the production differs across crop types, ENSO phases and the geographic areas. This chapter will predominantly discuss the countries that show evidence of a statistically significant causal relationship between ENSO and production; the complete set of results is available in the appendix.

5.1 Geographical distributions of the effect of ENSO on cereal production

5.1.1 Wheat

Results show the evidence of a statistically significant relationship between ENSO and the individual production response in 39 percent of main wheat producer countries. Figures 5.1and 5.2 illustrate this relationship. El Niño event was found responsible for wheat production variability in Argentina, the United States, Bulgaria and Morocco. During El Niño years, an apparent reduction in production happens in Morocco (26.4 percent) and in Bulgaria (13.4 percent). In contrast, El Niño events elevate wheat production in Argentina by 11.1 percent and in the United States by 4.9 percent. Positive impacts are often associated with cooler and wetter conditions in those countries (Iizumi, Luo et al. 2014). The countries affected by El Niño are responsible for 16 percent of global wheat production and 18 percent of wheat harvested area worldwide.

Of the two extreme phases of ENSO cycle, La Nina events appear to be more important in the ENSO-wheat production relationship. La Niña linkage is evident in Canada, Argentina, Spain, Italy, France, Hungary, Denmark, Austria, South Africa, Egypt, Syria and Saudi Arabia. Wheat production in the European countries, including Spain, Italy, France, Denmark, Hungary and Austria, increases during La Niña event ranges from 3.3 percent to 10.4 percent. Also, wheat production is enhanced in African countries including Egypt (5.5 percent) and South Africa (13.6 percent) during La Niña event, which should be a response to the wetter conditions in the most regions during this phase. Wheat production in Canada decreases by 15.1 percent, likely due to the lower temperature and less soil moisture content in La Niña years compared to normal years in Canada (Iizumi, Luo et al. 2014). Syria and Saudi Arabia show a tendency of reduced wheat production during La Niña for 14.8 and 8.5 percent, respectively. Figure 5.3 indicates the predicted effect of El Niño and La Niña on wheat production in the main producer countries. The statistically significant impact of La Niña on wheat production is found in countries responsible for 22 percent and 18 percent of global production and area harvested, respectively.

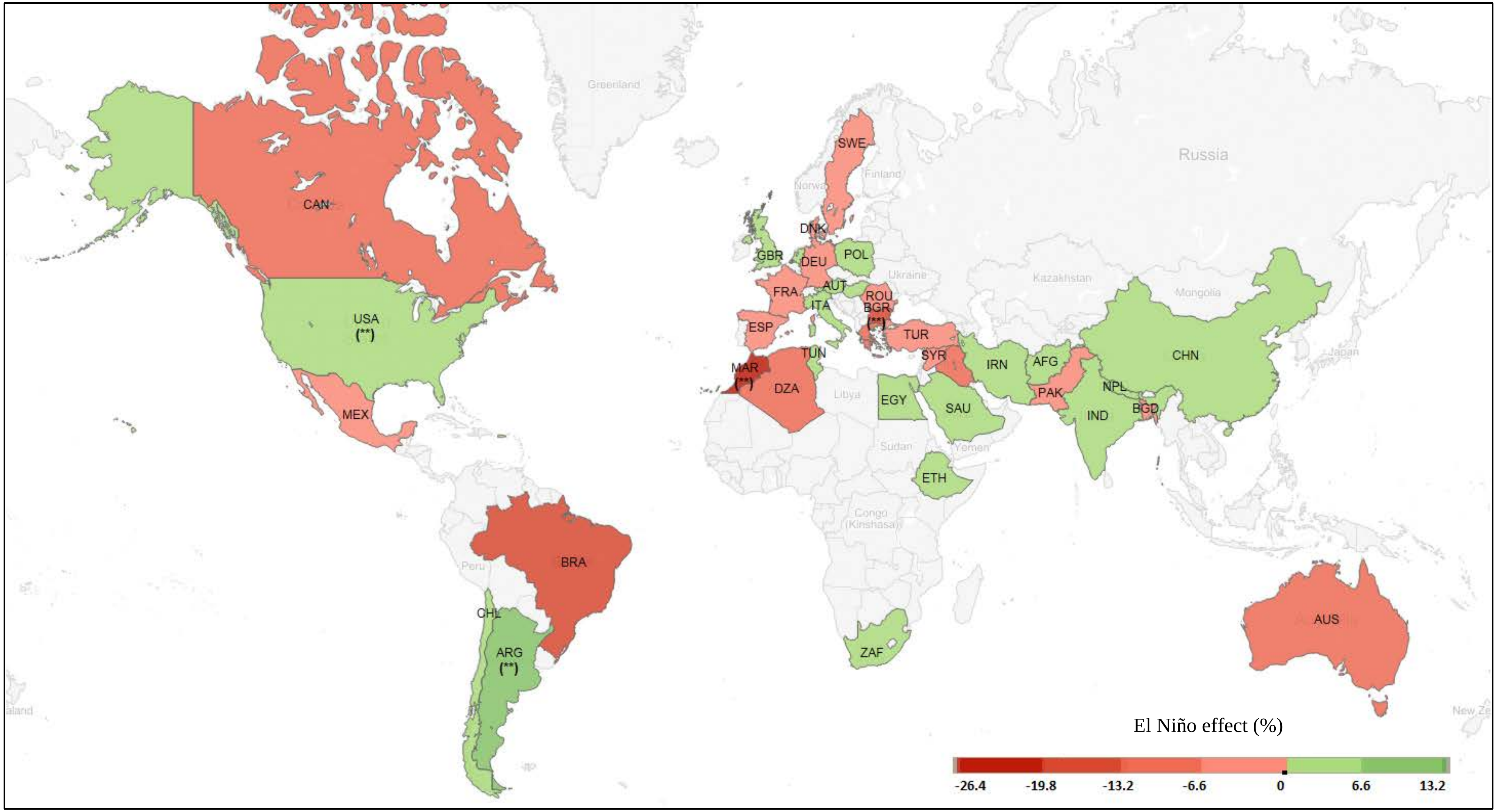

Figure 5.1. El Niño effect on wheat production.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

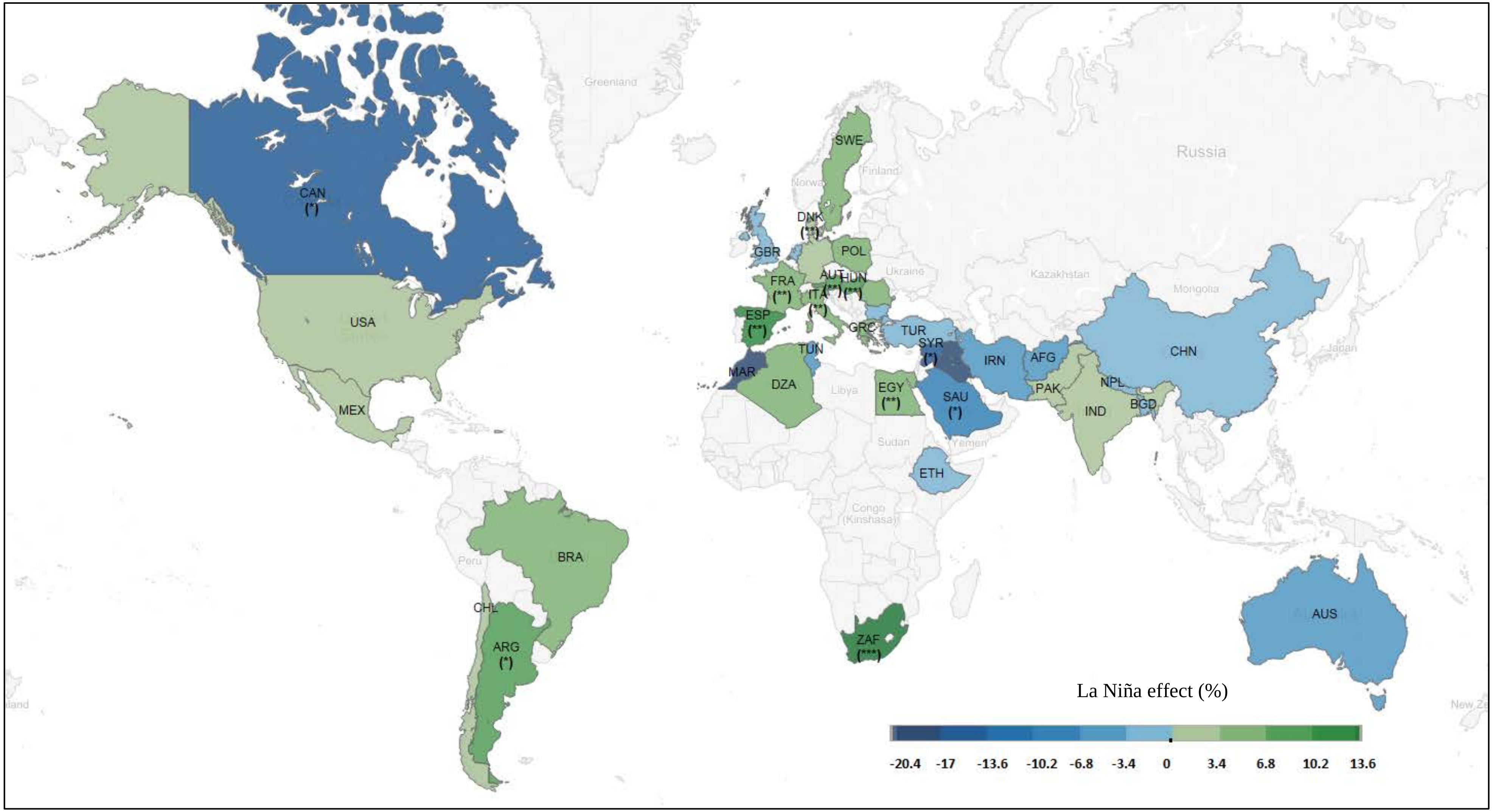

Figure 5.2. La Niña effect on wheat production.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

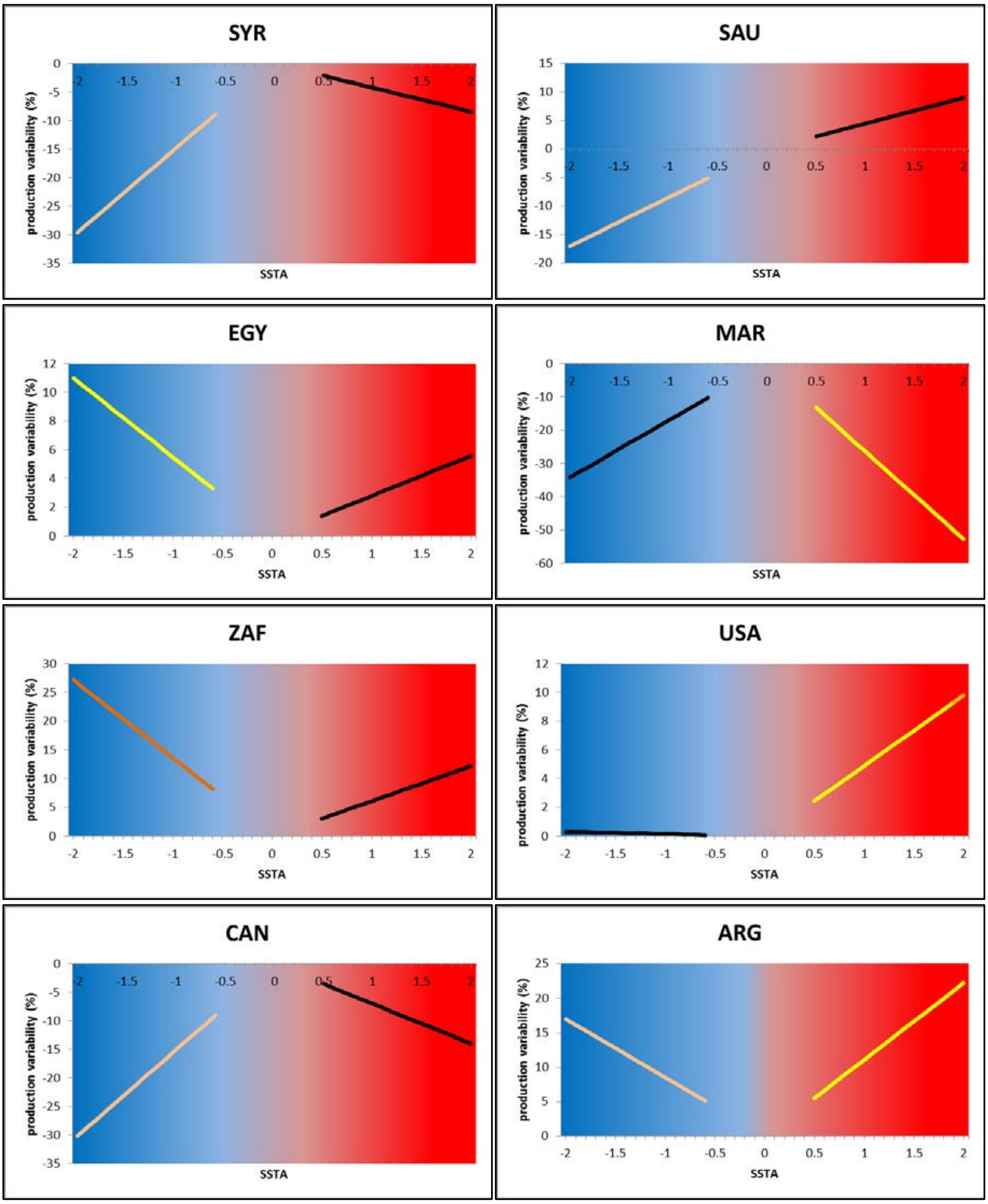

Figure 5. 3. Predicted effect of El Niño and La Niña on wheat production.

(— indicates insignificant effect, — indicates significant effect at 10% significance level, — indicates significant effect at 5% significance level, — and indicates significant effect at 1% significance level).

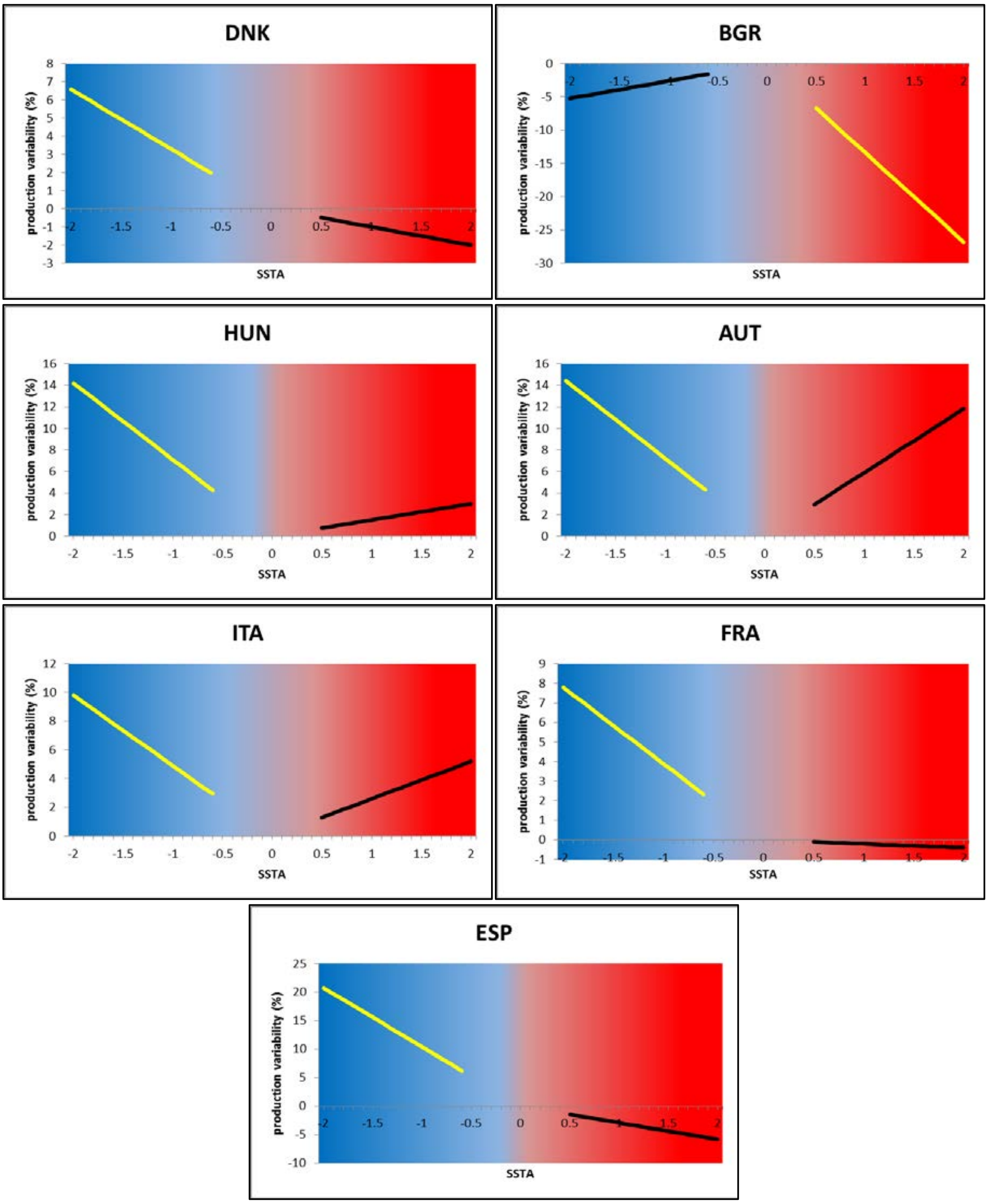

Figure 5. 3. Continued predicted effect of El Niño and La Niña on wheat production.

(—— indicates insignificant effect, —— indicates significant effect at 10% significance level, —— indicates significant effect at 5% significance level, —— and indicates significant effect at 1% significance level).

5.1.2 Maize

The analysis indicates that ENSO has statistically significant impact on production of 27 percent of major maize-producing countries. El Niño signals have significant impact on maize production in South Africa, the Philippines, Iran and Congo (Figure 5.4). La Niña significant impacts are evident in Brazil, Mexico, Thailand, Malawi, Zambia, Italy, Poland and Romania (Figure 5.5). Figure 5.6 indicates the predicted effect of El Niño and La Niña on maize production in the main producer countries.

El Niño positive correlation with maize production is apparent in Iran and Congo. Maize production increases by 13.3 percent and 1.7 percent in Iran and Congo, respectively. South Africa and the Philippines experience negative effect from the El Niño events. Dry and warm conditions in these areas during El Niño phases are often associated with negative impacts on maize production. The effect on South Africa is pronounced and is equal to 19.7 percent. Interestingly, although a large number of countries are affected by El Nino shocks, all together these countries account for only 6 percent of world area harvested, and 3 percent of world wheat production.

La Niña events are associated with increasing production in Brazil, Thailand, Malawi, Italy and Poland. Among countries which are positively associated with La Niña, the greatest impact for 16.1 percent is in Poland, then in Malawi (12.9 percent). La Niña is linked with rainfall enhance in Southeast Asia, most of Africa and Brazil. La Niña events likely decrease maize production in Zambia (11 percent), Romania (7.2 percent) and Mexico (6 percent). Significant impact of La Niña is found in countries that comprise almost 20 percent of global maize area harvested and 14 percent of total global production.

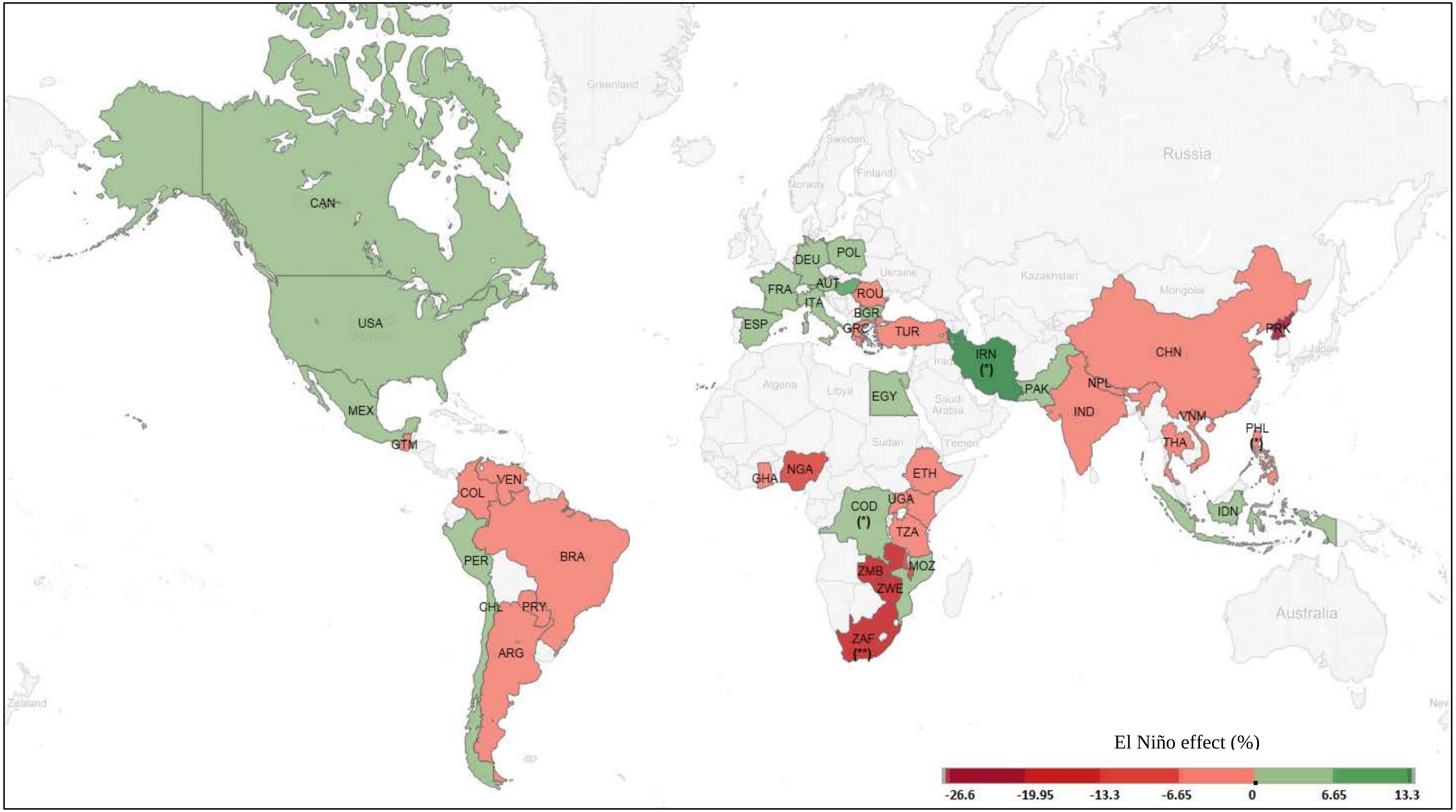

Figure 5.4. El Niño effect on maize production.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

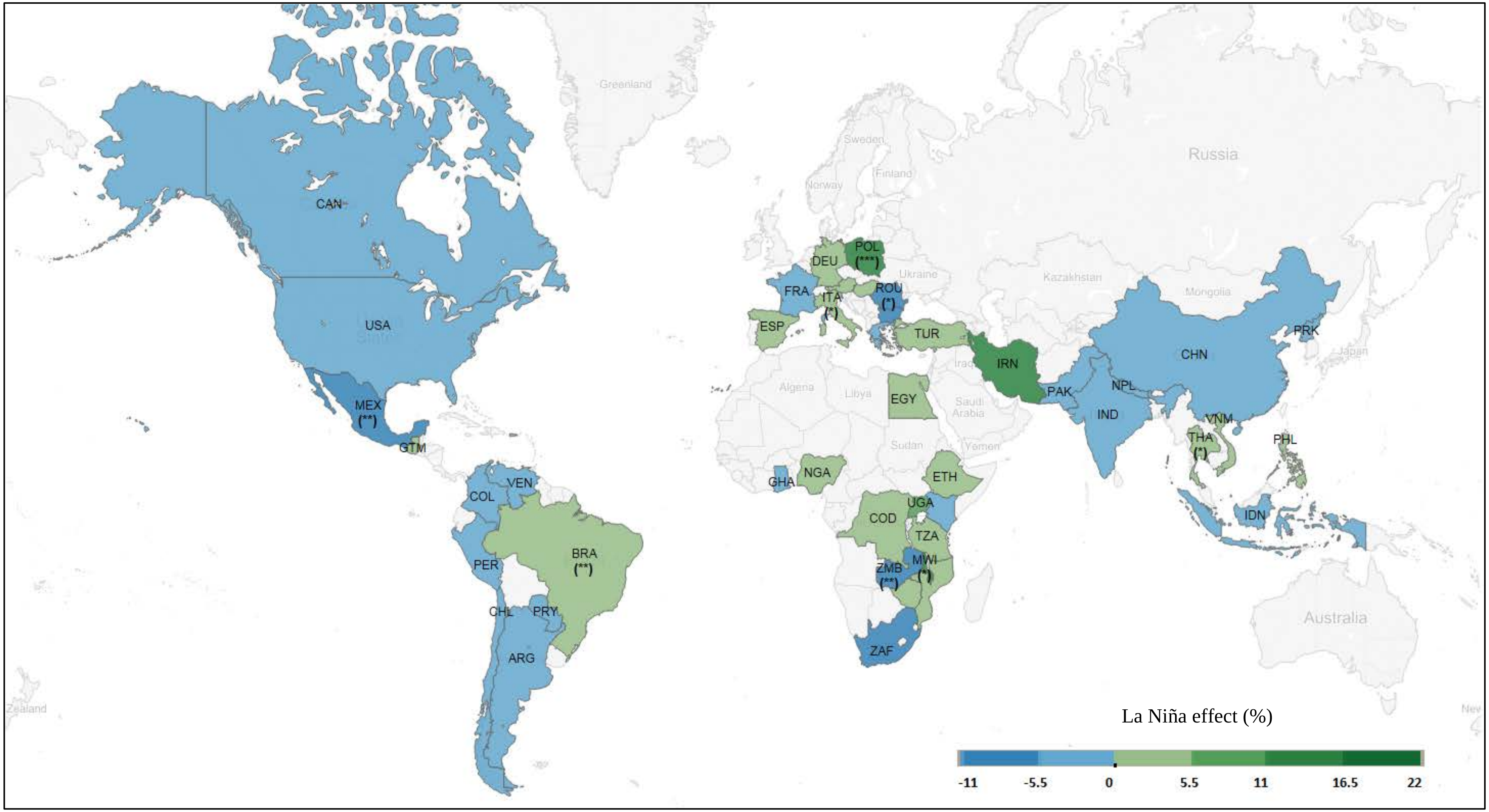

Figure 5.5. La Niña effect on maize production.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

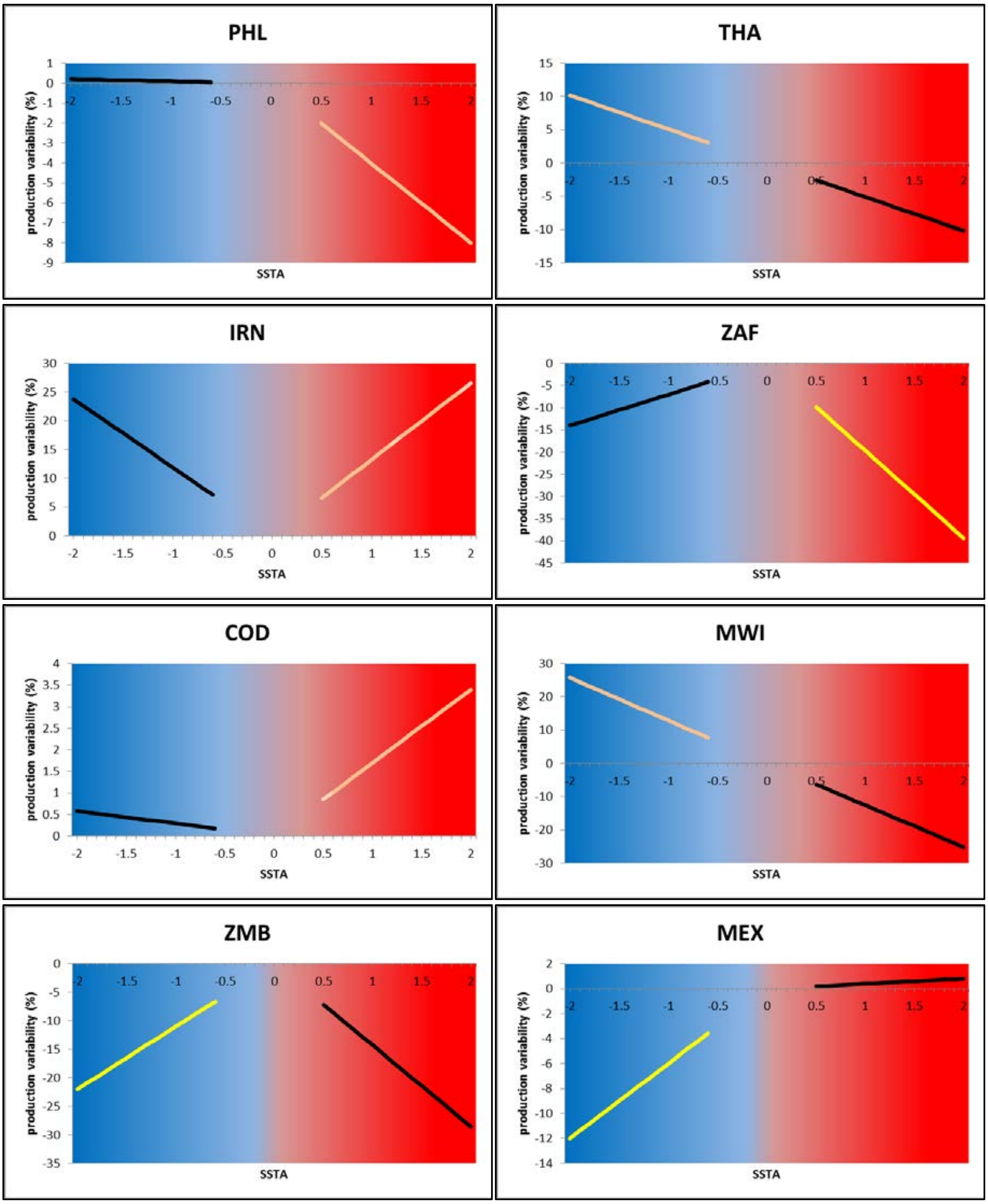

Figure 5.6. Predicted effect of El Niño and La Niña on maize production.

(——— indicates insignificant effect, ——— indicates significant effect at 10% significance level, ——— indicates significant effect at 5% significance level, ——— and indicates significant effect at 1% significance level).

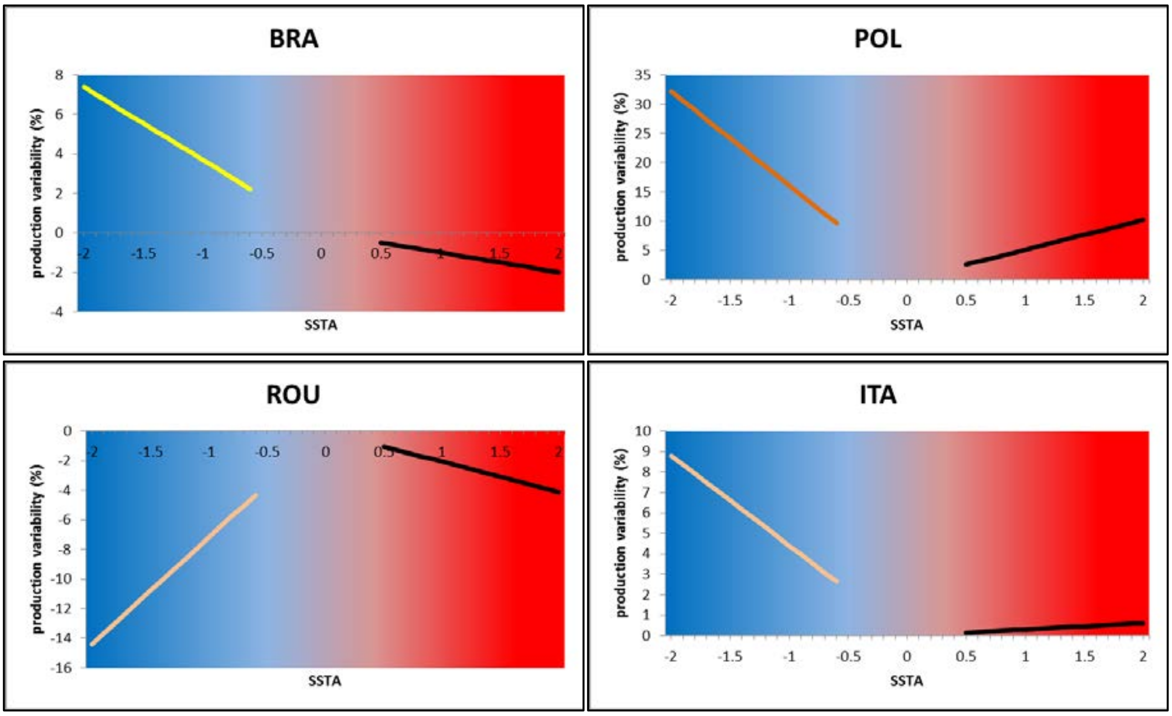

Figure 5.6. Continued predicted effect of El Niño and La Niña on maize production.

(——— indicates insignificant effect, ——— indicates significant effect at 10% significance level, ——— indicates significant effect at 5% significance level, ——— and indicates significant effect at 1% significance level).

5.1.3 Rice

We find evidence of a statistically significant relationship between ENSO and rice production in 23 percent of the main producer countries (Figures 5.7 and 5.8). Figure 5.9 indicates the predicted effect of ENSO on rice production in the major producer countries.

Not surprisingly, El Niño events are associated with rice production reduction in Indonesia (by 3.7 percent) and Bangladesh (by 2.9 percent). El Niño-related warm and dry weather shocks result in rice production reduction in South and Southeast Asia. El Niño event reduces rice production in Brazil by 4.5 percent. El Niño phase leads to dry and warm weather in Brazil which is responsible for rice production reduction. Rice production, also, decreases in North Korea, Spain and Côte d’Ivoire ranges from 2.1 percent to 12.3 percent during El Niño events. Nicaragua is the only country that rice production is positively affected by El Niño phase (10.7 percent). El Niño events affect countries that totally cover 28 percent of worldwide rice area harvested and 18 percent of world production.

The Philippines, Cambodia, Nicaragua and Vietnam are the countries where the correlation between rice production and La Niña event is significant. During La Niña years rice production in Cambodia increases by 14.7 percent. In Vietnam rice production rises by 7.2 percent during La Niña events. This production increase is consistent with La Nina-induced wetter condition in Southeast Asia. La Nina-related negative effect is apparent in the Philippines (4.8 percent) and Nicaragua (6.5 percent). Although rainfall increases during the ENSO cold phase, this production reduction could be associated with the occurrence of floods. The La Niña signal is significant in 9 percent of global rice area harvested that producing 9 percent of rice production.

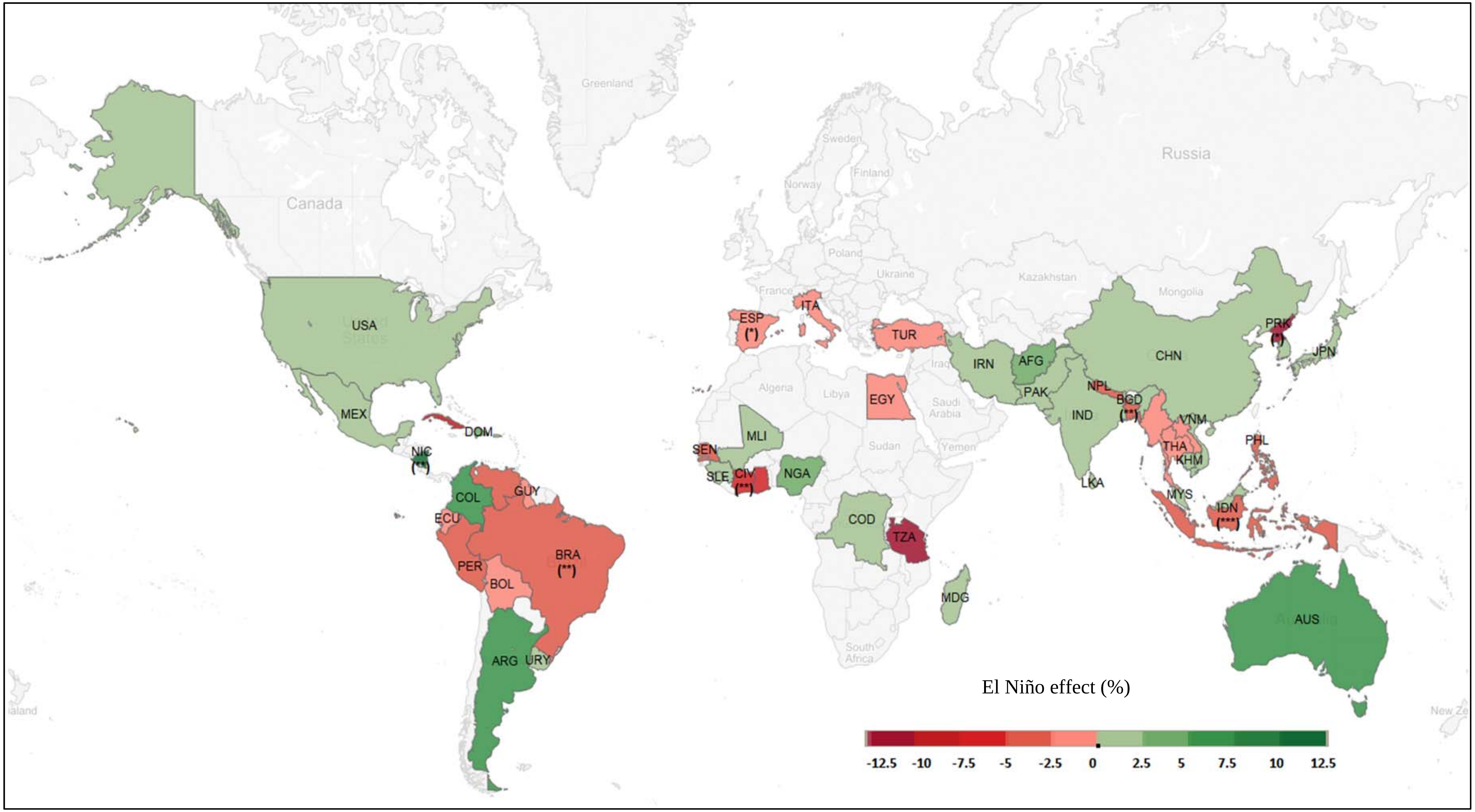

Figure 5.7. El Niño effect on rice production.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

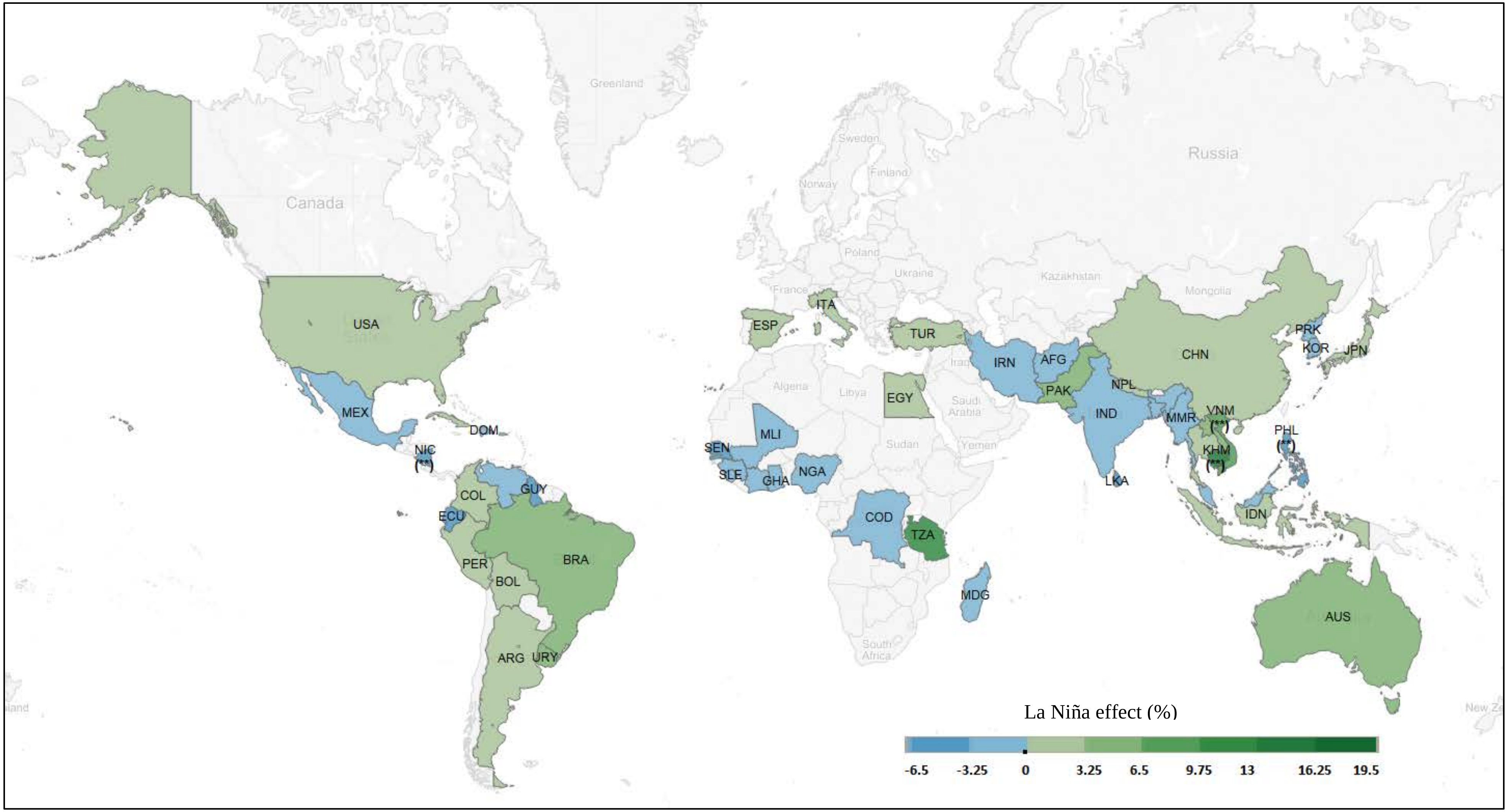

Figure 5.8. La Niña effect on rice production.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

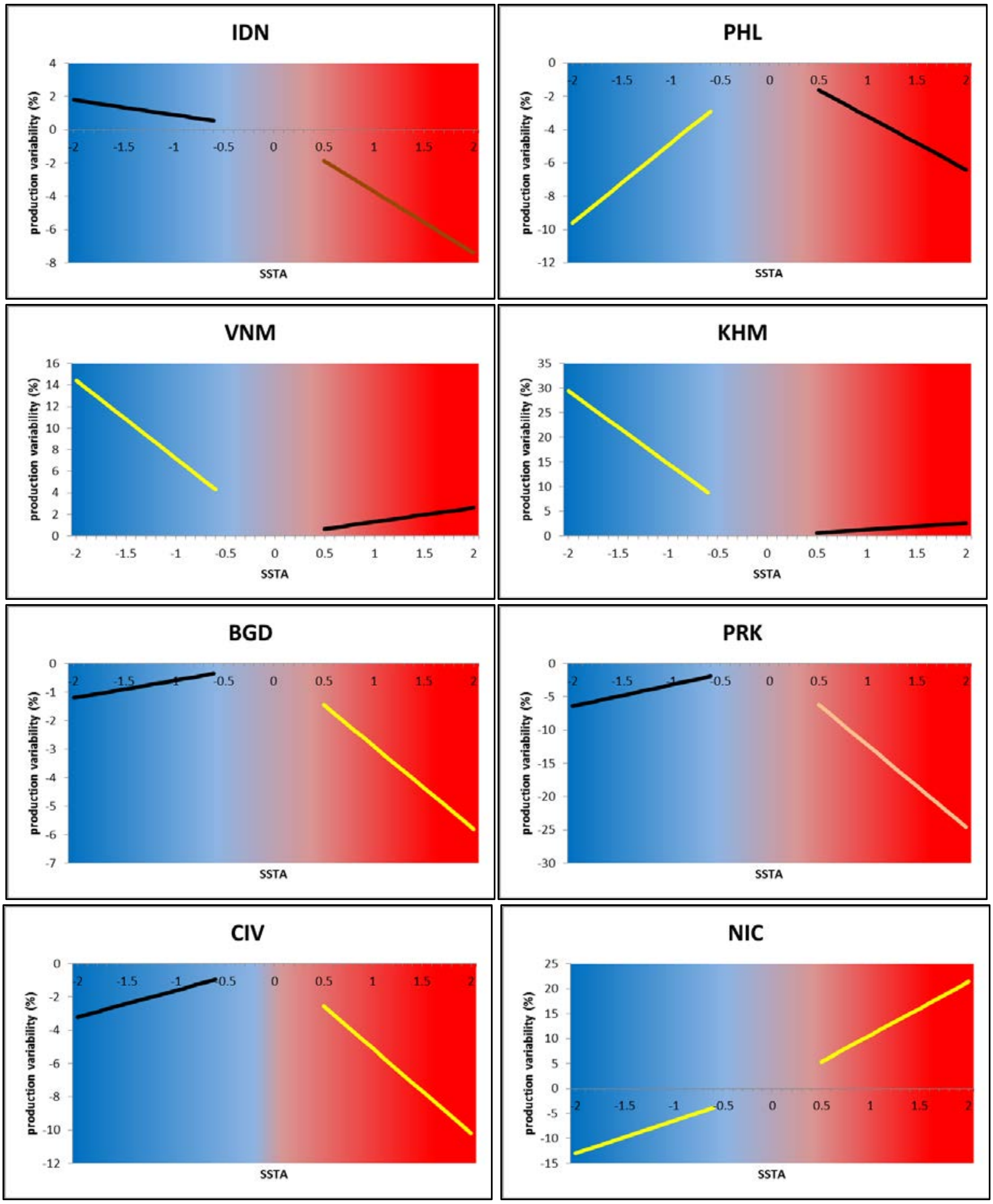

Figure 5.9. Predicted effect of El Niño and La Niña on rice production.

(—— indicates insignificant effect, —— indicates significant effect at 10% significance level, —— indicates significant effect at 5% significance level, —— and indicates significant effect at 1% significance level).

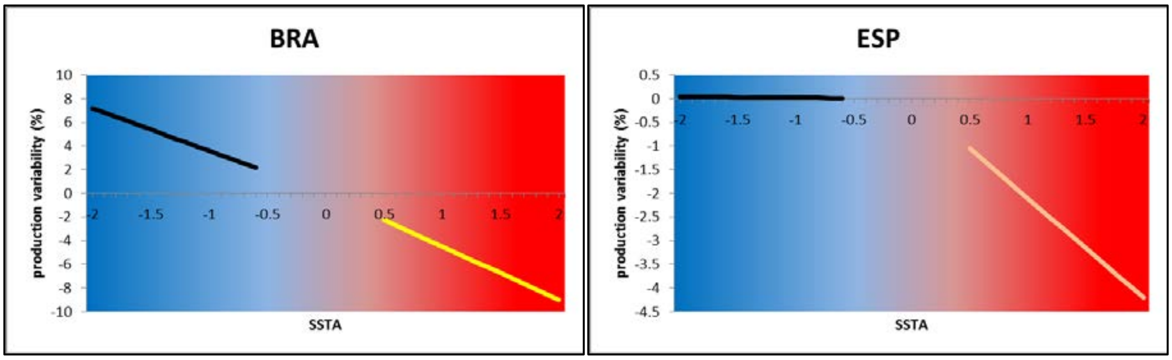

Figure 5.9. Continued predicted effect of El Niño and La Niña on rice production.

(——— indicates insignificant effect, ——— indicates significant effect at 10% significance level, ——— indicates significant effect at 5% significance level, ——— and indicates significant effect at 1% significance level).

5.2 The effect of ENSO on world cereal production

Two key aspects become clear from the foregoing discussion. First of all, ENSO shocks impact world cereal production in many regions of the world. Second, these effects are largely heterogeneous. The impact of ENSO on global production uses country-level parameter estimates associated with the ENSO variables which are weighted by share of the production of a particular country in the world. The ENSO impacts on global production vary across ENSO phase and crop type. On a global scale, findings suggest that during El Niño years, global rice and maize production decreases by approximately 0.09 percent and 0.11 percent, respectively. On the contrary, wheat production increases by 0.18 percent during El Niño event. In contrast, La Niña episodes result in a reduction of wheat production (0.01 percent) and maize production (0.77 percent) but in an increase of rice production (0.71 percent). Importantly, these effects are net of precipitation and temperature, which are known to vary with ENSO phases. That is, findings of this study suggest that there are effects associated with ENSO events above and beyond these weather variables. Such “extreme” effects, in turn, may include: (i) ENSO-related hazardous weather conditions like severe drought, flooding, storms and wildfire (Changnon 1999), (ii) ENSO-amplified pest damages (insects, bacteria, fungi and nematodes) (Rosenzweig, Iglesias et al. 2000).

Chapter 6. Discussion

Our analyses of ENSO records show that the El Niño effect on cereal production, while typically negative, can also be positive in many regions. The southern hemisphere usually receives more severe effects. ENSO impacts also differ by geographical area. For instance, consider the United States and Brazil; the two countries that expand over large and distinct geographical areas. It turns out that they are both affected by ENSO phenomena, though effect is in opposite directions. That is, ENSO-induced increase in crop production of one country is offset by the crop reduction in another country. Also, ENSO impact varies by crop. Tables 6.1 and 6.2 present the production variability in different regions of the world during El Niño and La Niña events, respectively. An El Niño event generates wheat production increase in East Africa, South Asia, Middle Europe and South America. While in the same phase of ENSO, most countries in Africa, East and Southeast Asia, and East America experience reduction in maize production. And, rice production reduces in Southeast and West Asia, Europe and most countries in South America, during the El Niño phase. Accordingly, wheat production change during El Niño years in the world is positive, but changes in maize and rice production are negative.

Table 6.1. Cereal production variability during El Niño event

Country /Region	Wheat			Maize			Rice			Total Cereal Production Change (000 tonnes)
	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	
South Asia		111510.8	340.3		20870.1	-426.8		191655.2	-258.7	-345.2
Afghanistan	4	3202.8	128.1				3.7	459	17	145.1
Bangladesh	-3.3	1252.7	-41.3				-2.9	38970.2	-1130.1	-1171.4
India	0.4	74026.8	296.1	-4.5	15121.1	-680.4	0.6	135219.1	811.3	427
Nepal	1.3	1323	17.2	-0.86	1634.3	-14.1	-3.5	4076.8	-142.7	-139.6
Pakistan	-1.3	20336.1	-264.4	2.7	2637.6	71.2	2	7234.5	144.7	-48.5
Sri Lanka							0.1	3168.3	3.2	3.2
Iran	1.8	11369.4	204.6	13.3	1477.1	196.5	1.5	2527.3	37.9	439
Southeast Asia					25393.5	-467.3		168129.8	-2525.2	-2992.5
Cambodia							1.3	5515.7	71.7	71.7
Indonesia				0.6	12426.6	74.6	-3.7	56000.9	-2072	-1997.4
Lao People's Democratic Republic							-2.5	2440	-61	-61
Malaysia							0.5	2277.8	11.4	11.4
Myanmar							-1.1	24728.5	-272	-272
Philippines				-4	5454.5	-218.2	-3.2	13938.2	-446	-664.2
Thailand				-5.1	4381.6	-223.5	-0.71	28820.5	-204.6	-428.1
Viet Nam				-3.2	3130.8	-100.2	1.3	34408.2	447.3	347.1
East Asia		106978.4	3209.4		144800.7	-4096.9		210747	2683.5	1796
China	3	106978.4	3209.4	-2.6	143148.5	-3721.9	1.5	190406.2	2856.1	2343.6
Democratic People's Republic of Korea				-22.7	1652.2	-375	-12.3	2307.1	-283.8	-658.8
Japan							0.8	11427.7	91.4	91.4
Republic of Korea							0.3	6606	19.8	19.8
West Asia		27192.4	-944.7		3195.4	-147		526.5	-8.4	-1100.1
Iraq	-8.7	1859	-161.7							-161.7
Saudi Arabia	4.5	1878.2	84.5							84.5
Syrian Arab Republic	-4.2	3854.7	-161.9							-161.9
Turkey	-3.6	19600.5	-705.6	-4.6	3195.4	-147	-1.6	526.5	-8.4	-861
South America		18620.4	921.7		69588.9	-995.4		21315.9	-499.9	-573.6
Argentina	11.1	13201.5	1465.4	-2.8	17586.8	-492.4	5.9	1129.5	66.6	1039.6
Bolivia							-0.6	355.4	-2.1	-2.1
Brazil	-14.4	3930.3	-566	-1	44866	-448.7	-4.5	11103.4	-499.7	-1514.4
Chile	1.5	1488.6	22.3	3.4	1132.7	38.5				60.8
Colombia				-0.4	1379.1	-5.5	6.9	2075.4	143.2	137.7
Cuba							-8.3	529.9	-44	-44
Ecuador							-1.2	1423.9	-17.1	-17.1
Guyana							-2.49	530.4	-13.2	-13.2
Paraguay				-3.64	1601.5	-58.3				-58.3

Table 6.1. Continued cereal production variability during El Niño event

Country /Region	Wheat			Maize			Rice			Total Cereal Production Change (000 tonnes
	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	
Peru				1.67	1239.9	20.7	-4.5	2156.4	-97	-76.3
Uruguay							0.3	1142.4	3.4	3.4
Venezuela				-2.79	1782.9	-49.7	-4.6	869.2	-40	-89.7
North, Central America and the Caribbean		88010.8	1030.3		303608.1	7638		10379.7	96	8764.3
Canada	-7	25183.7	-1762.9	2.3	9484.5	218.1				-1544.8
Dominican Republic							4.5	658.5	29.6	29.6
Guatemala				-1.9	1268.8	-24.1				-24.1
Mexico	-3.5	3396.4	-118.9	0.4	20133.4	80.5	0.54	298.6	1.6	-36.8
Nicaragua							10.7	298.9	32	32
United States of America	4.9	59430.7	2912.1	2.7	272721.4	7363.5	0.36	9123.7	32.8	10308.4
Africa		18596.3	-910.4		43076	-3271.3		18489.2	-58.1	-4239.8
Cote D'Ivoire							-5.1	804.1	-41	-41
Guinea							0.32	1283.1	4.1	4.1
Madagascar							1.1	3229.5	35.5	35.5
Mali							0.9	1123.4	10.1	10.1
Senegal							-2.7	282.8	-7.6	-7.6
Sierra Leone							2	625.3	12.5	12.5
Uganda				-4.4	1496.9	-65.9				-65.9
Egypt	2.8	7089.2	198.5	1.7	6481.1	110.2	-0.9	5722.3	-51.5	257.2
Ghana				-0.3	1288.1	-3.9	-6	294.3	-17.7	-21.6
Nigeria				-7.3	6402.9	-467.4	4.1	3572.8	146.5	-320.9
United Republic of Tanzania				-6	3446.3	-206.8	-12.5	1216.3	-152	-358.8
Morocco	-26.4	4146	-1094.5							-1094.5
Tunisia	0.2	1229.3	2.5							2.5
South Africa	6.1	2021	123.3	-19.7	10039.9	-1977.9				-1854.6
Ethiopia	0.3	1961.7	5.9	-0.9	3585.3	-32.3				-26.4
Mozambique				6.6	1261.7	83.3				83.3
Zambia				-14.3	1418.3	-202.8				-202.8
Zimbabwe				-13.5	1339.5	-180.8				-180.8
Kenya				-1.8	2783.4	-50.1				-50.1
Malawi				-12.6	2356	-296.9				-296.9
Algeria	-6.8	2149.1	-146.1							-146.1
Democratic Republic of Congo				1.7	1176.6	20	0.9	335.3	3	23

Table 6.1. Continued cereal production variability during El Niño event

Country /Region	Wheat			Maize			Rice			Total Cereal Production Change (000 tonnes)
	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	El Niño Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	
Europe		119561.7	-971.1		54833.2	1027.6		2203.3	-44.9	11.6
Austria	5.9	1435.5	84.7	1	1829.9	18.3				103
Bulgaria	-13.4	3582.6	-480.1	5.5	1502.7	82.6				-397.5
Denmark	-1	4702.4	-47							-47
France	-0.2	36075.1	-72.2	2.8	14865.6	416.2				344
Germany	-1	21763.2	-217.6	1.2	3754.3	45.1				-172.5
Greece	-8.4	1981.4	-166.4	-1.8	2203.9	-39.7				-206.1
Hungary	1.5	4418.3	66.3	7.8	6582.9	513.5				579.8
Italy	2.6	7461.7	194	0.3	9357	28.1	-2	1423.9	-28.5	193.6
Poland	0.8	8832.8	70.7	5.1	1569.4	80				150.7
Romania	-5.3	5735.5	-304	-2.07	9236.1	-191.2				-495.2
Spain	-2.9	5688.1	-165	1.9	3931.4	74.7	-2.1	779.4	-16.4	-106.7
United Kingdom	0.8	14626.6	117							117
Sweden	-4.4	2094.8	-92.2							-92.2
Netherlands	3.5	1163.7	40.7							40.7
Oceania		20739	-1742.1					839.7	43.7	-1698.4
Australia	-8.4	20739	-1742.1				5.2	839.7	43.7	-1698.4
World		511209.8	933.4		665365.9	-739.1		624286.3	-572	-377.7

Table 6.2. Cereal production variability during La Niña event

Country /Region	Wheat			Maize			Rice			Total Cereal Production Change (000 tonnes)
	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	
South Asia		111510.8	1285.8		20870.1	54.5		191655.2	-725.6	614.7
Afghanistan	-6.5	3202.8	-208.2				-0.3	459	-1.4	-209.6
Bangladesh	-0.04	1252.7	-0.5				-0.6	38970.2	-233.8	-234.3
India	2.5	74026.8	1850.7	-0.7	15121.1	-105.8	-0.6	135219.1	-811.3	933.6
Nepal	-0.6	1323	-7.9	-0.3	1634.3	-4.9	0.49	4076.8	20	7.2
Pakistan	0.3	20336.1	61	-0.4	2637.6	-10.6	5.8	7234.5	419.6	470
Sri Lanka							-3.7	3168.3	-117.2	-117.2
Iran	-3.6	11369.4	-409.3	11.9	1477.1	175.8	-0.06	2527.3	-1.5	-235
Southeast Asia					25393.5	205		168129.8	3100.7	3305.7
Cambodia							14.7	5515.7	810.8	810.8
Indonesia				-1.1	12426.6	-136.7	0.9	56000.9	504	367.3
Lao People's Democratic Republic							3.5	2440	85.4	85.4
Malaysia							-2	2277.8	-45.6	-45.6
Myanmar							-2	24728.5	-494.6	-494.6
Philippines				0.1	5454.5	5.5	-4.8	13938.2	-669	-663.5
Thailand				5.1	4381.6	223.5	1.5	28820.5	432.3	655.8
Viet Nam				3.6	3130.8	112.7	7.2	34408.2	2477.4	2590.1
East Asia		106978.4	-534.9		144800.7	-1647.3		210747	1525.6	-656.6
China	-0.5	106978.4	-534.9	-1.1	143148.5	-1574.6	0.8	190406.2	1523.2	-586.3
Democratic People's Republic of Korea				-4.4	1652.2	-72.7	-3.2	2307.1	-73.8	-146.5
Japan							0.8	11427.7	91.4	91.4
Republic of Korea							-0.23	6606	-15.2	-15.2
West Asia		27192.4	-1616.2		3195.4	79.9		526.5	15.3	-1521
Iraq	-19.2	1859	-356.9							-356.9
Saudi Arabia	-8.5	1878.2	-159.6							-159.6
Syrian Arab Republic	-14.8	3854.7	-570.5							-570.5
Turkey	-2.7	19600.5	-529.2	2.5	3195.4	79.9	2.9	526.5	15.3	-434
South America		18620.4	1372.4		69588.9	774.5		21315.9	468.1	2615
Argentina	8.5	13201.5	1122.1	-4.6	17586.8	-809	2.4	1129.5	27.1	340.2
Bolivia							2.8	355.4	10	10
Brazil	5.8	3930.3	228	3.7	44866	1660	3.6	11103.4	399.7	2287.7
Chile	1.5	1488.6	22.3	-1.3	1132.7	-14.7				7.6
Colombia				-1.8	1379.1	-24.8	2.2	2075.4	45.7	20.9
Cuba							2.6	529.9	13.8	13.8

Table 6.2. Continued cereal production variability during La Niña event

Country /Region	Wheat			Maize			Rice			Total Cereal Production Change (000 tonnes)
	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	
Ecuador							-4.8	1423.9	-68.3	-68.3
Guyana							-3.3	530.4	-17.5	-17.5
Paraguay				-0.2	1601.5	-3.2				-3.2
Peru				-2.3	1239.9	-28.5	0.9	2156.4	19.4	-9.1
Uruguay							3.8	1142.4	43.4	43.4
Venezuela				-0.3	1782.9	-5.3	-0.6	869.2	-5.2	-10.5
North, Central America and the Caribbean		88010.8	-3704.2		303608.1	-4776.4		10379.7	5.4	-8475.2
Canada	-15.1	25183.7	-3802.7	-3.6	9484.5	-341.4				-4144.1
Dominican Republic							-0.5	658.5	-3.3	-3.3
Guatemala				3.6	1268.8	45.7				45.7
Mexico	0.1	3396.4	3.4	-6	20133.4	-1208	-2.8	298.6	-8.4	-1213
Nicaragua							-6.5	298.9	-19.4	-19.4
United States of America	0.16	59430.7	95.1	-1.2	272721.4	-3272.7	0.4	9123.7	36.5	-3141.1
Africa		18596.3	-18.1		43076	256.2		18489.2	-11	227.1
Cote D'Ivoire							-1.6	804.1	-12.9	-12.9
Guinea							-0.4	1283.1	-5.1	-5.1
Madagascar							-0.9	3229.5	-29.1	-29.1
Mali							-2.7	1123.4	-30.3	-30.3
Senegal							-6.4	282.8	-18.1	-18.1
Sierra Leone							-2.5	625.3	-15.6	-15.6
Uganda				10.3	1496.9	154.2				154.2
Egypt	5.5	7089.2	389.9	0.41	6481.1	26.6	1.5	5722.3	85.8	502.3
Ghana				-3	1288.1	-38.6	-2.2	294.3	-6.5	-45.1
Nigeria				5.3	6402.9	339.4	-3.2	3572.8	-114.3	225.1
United Republic of Tanzania				5.2	3446.3	179.2	11.6	1216.3	141.1	320.3
Morocco	-17.1	4146	-709							-709
Tunisia	-3.9	1229.3	-47.9							-47.9
South Africa	13.6	2021	274.9	-7	10039.9	-702.8				-427.9
Ethiopia	-2.8	1961.7	-54.9	2.5	3585.3	89.6				34.7
Mozambique				4.1	1261.7	51.7				51.7
Zambia				-11	1418.3	-156				-156
Zimbabwe				4.8	1339.5	64.3				64.3
Kenya				-2.1	2783.4	-58.5				-58.5
Malawi				12.89	2356	303.7				303.7
Algeria	6	2149.1	128.9							128.9
Democratic Republic of Congo				0.29	1176.6	3.4	-1.8	335.3	-6	-2.6

Table 6.2. Continued cereal production variability during La Niña event

Country /Region	Wheat			Maize			Rice			Total Cereal Production Change (000 tonnes)
	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	La Niña Effect (%)	Mean Annual Production (000 tonnes)	Production Variability (000 tonnes)	
Europe		119561.7	4028.9		54833.2	-85		2203.3	13	3956.9
Austria	7.2	1435.5	103.4	0.6	1829.9	11				114.4
Bulgaria	-2.6	3582.6	-93.1	-9.7	1502.7	-145.8				-238.9
Denmark	3.3	4702.4	155.2							155.2
France	3.9	36075.1	1406.9	-2.9	14865.6	-431.1				975.8
Germany	2.5	21763.2	544.1	3.3	3754.3	123.9				668
Greece	4.8	1981.4	95.1	-3.4	2203.9	-74.9				20.2
Hungary	7.1	4418.3	313.7	4.6	6582.9	302.8				616.5
Italy	4.9	7461.7	365.6	4.4	9357	411.7	0.9	1423.9	12.8	790.1
Poland	3.5	8832.8	309.1	16.1	1569.4	252.7				561.8
Romania	3.6	5735.5	206.5	-7.2	9236.1	-665				-458.5
Spain	10.4	5688.1	591.6	3.3	3931.4	129.7	0.02	779.4	0.2	721.5
United Kingdom	-0.4	14626.6	-58.5							-58.5
Sweden	5.1	2094.8	106.8							106.8
Netherlands	-1.5	1163.7	-17.5							-17.5
Oceania		20739	-891.8					839.7	30.2	-861.6
Australia	-4.3	20739	-891.8				3.6	839.7	30.2	-861.6
World		511209.8	-78.1		665365.9	-5138.6		624286.3	4421.7	-795

As a result, during El Niño phase, the total cereal production change, on global scale, is negative. During La Niña events, wheat production in North America, most of Asia, and Australia decreases. Also, La Niña results in maize production reduction in most American and Asian countries. Rice production tends to show positive responses in La Niña years; most apparently in North and South America, most parts of East, Southeast and West Asia, and Australia. La Niña phases make rise to global rice production, whereas global wheat and maize production decrease during La Niña phases. Global cereal production experiences a negative change during La Niña events. Consequently, minimizing the ENSO negative effects also getting benefit from the ENSO positive impact on global cereal production could be an important tool to ensure food availability during ENSO years.

6.1 Comparisons of this study with previous global and regional studies

The results of this study support the general hypothesis that ENSO impacts the production of wheat, maize and rice, on both a regional and global basis. Here, we discuss our results and compare them with previous similar studies. Tables 6.3 and 6.4 present a summary of the comparison between the results of this study and other global and regional studies, respectively. Here, the countries that exhibit a statistically significant causal relationship between ENSO and production are discussed in more detail.

A large number of previous studies examine the ENSO impact on cereal production for a specific region or country (e.g. Pol and Binyamin (2014), and Roberts, Dawe et al. (2009), Royce, Fraisse et al. (2011). However, few studies examine the impact of ENSO on cereal production from a global perspective. Chen and McCarl (2000) estimate the ENSO impact on crop production in the main producing countries by applying a stochastic model coupled with a global trade model. Chen, McCarl et al. (2008) study the ENSO impact on major rice producing countries. They apply a regression approach with non-climate-related variables as explanatory variables. Their model links total rice production to the planting area and trend (technology) variables. To reflect the ENSO effect on rice production, they use the deviations from average production that are grouped by ENSO phases. Iizumi, Luo et al. (2014) present the global impact of ENSO on the yield of major cereals including wheat, maize and rice. They first calculate the percentage yield anomaly, which is calculated as the deviation from a normal yield. Then they determine the average of percentage yield anomalies for El Niño, La Niña and normal years over the period of 1984–2004. Finally, the percentage yield anomalies of particular crops are weighted by the production ratio in each different cropping system.

In this study, we first investigate the country-level correlation between the El Niño-Southern Oscillation (ENSO) and cereal production. Then, the ENSO impact on world cereal production is estimated using the country-level ENSO-related effects and the global production ratio of a particular crop. The distinctive approaches of this study compared to other studies include the following:

- It applies a regression-based approach to directly estimate the ENSO impact on crop production. Also, the threshold regression (TR) analysis allows for asymmetric production responses to the warm and cold ENSO phases.
- It incorporates weather variables, such as temperature and precipitation, in the regression setting, to capture the "additional" ENSO effect on crop production, net of climatic effect. In so doing, ENSO variable serves as a proxy for natural disasters and anomalies, not otherwise captured by average rainfall and temperature variables.
- It incorporates lagged price (as a proxy for expected price) of the considered commodity in the regression setting to control for an important economic variable affecting crop supply and to isolate the ENSO impact from the price-related production variability.
- It uses time series data spanning 1962-2009 (48 years), which includes more ENSO events than the time series used in majority of previous similar studies.

Examining the effect of El Niño or La Niña net of all other factors is an important distinction of this study, compared to the previous studies, which look at aggregate climate effect (including rainfall and temperature) during El Niño and La Niña years. The different spatial effect of ENSO between this study and previous ones mainly goes back to the procedure of capturing the net effect of ENSO on crop production. Nonetheless, the results of this study, in terms of the signs of the El Niño or La Niña impacts (positive or negative) across the countries and crops, are similar to many of the previous studies. However, one example of discrepancy is the ENSO effect on wheat in the U.S. The result of this study shows that El Niño causes a positive, significant effect on wheat production. In contrast, Iizumi, Luo et al. (2014) show that El Niño causes a negative effect. Iizumi, Luo et al. (2014) define the index of ENSO based on the reproductive growth period of wheat, including both winter and spring cropping systems. Our study contributes winter wheat crop calendar since it is responsible for the highest area harvested. Izaurralde, Rosenberg et al. (1999) find that both the positive and negative impacts on wheat yield across different regions in the U.S. Hansen, Jones et al. (2001) examine the ENSO effect on wheat yield in a specific region in the U.S. The U.S.'s large share of global wheat production, and methodological differences across the two studies, is responsible for the discrepancy between our results (which are from a global perspective) and the results of Iizumi, Luo et al. (2014).

Table 6.3. Comparison in the effect of ENSO on global cereal production/yield between this study and previous studies

Crop	This study		Iizumi, Luo et al. (2014)		Chen, McCarl et al. (2008)		Chen and McCarl (2000)	
	El Niño effect(1)	La Niña effect(1)	El Niño effect(1)	La Niña effect(1)	El Niño effect(1)	La Niña effect(1)	El Niño effect(1)	La Niña effect(1)
Wheat	+	-	-	-	N.A.	N.A.	+/-	+
Maize	-	-	-	-	N.A.	N.A.	-	-
Rice	-	+	-	-	-	-	N.A.	N.A.

(1):"+" and "-" indicate the positive and negative impacts on global production, respectively.

"N.A." indicates the data are not available from references.

Table 6.4. Comparison in the effect of ENSO on crop production/yield between this study and previous studies

Crop	This study			Previous study						
	Country	El Niño effect(1)	La Niña effect(1)	Country /Region	El Niño effect(1)	La Niña effect(1)	ENSO Index(2)	Regression estimated(3)	Data time interval	References
Wheat	Argentina	(+)	(+)	Argentina	(+)/(-)	(+)/(-)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				Buenos Aires	(-)	(-)	SOI	×	1997-1998* 2007-2008* (case study)	Pol and Binyamin (2014)
				Buenos Aires	(+)	(-)	SSTA Niño3	✓	1950–1994	Travasso, Magrin et al. (2003)
				Argentina	+	-	N.A.	×	1972-1993	Chen and McCarl (2000)
Wheat	Australia	-	-	Australia (eastern)	(-)	(-)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				Australia	-	-	N.A.	×	1972-1993	Chen and McCarl (2000)
				Australia (eastern)	(-)	-	SOI	×	1886- 1993	Meinke and Stone (1997)
				Australia	(-)	(+)	SOI	✓	1948 -1988	Rimmington and Nicholls (1993)
Wheat	Canada	-	(-)	Canada	(+)/(-)	(-)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				Canada	(+)/(-)	N.A.	JMA	×	1968 -1994	Izaurralde, Rosenberg et al. (1999)
				Canada	+	-	N.A.	×	1972-1993	Chen and McCarl (2000)

Table 6.4. Continued comparison in the effect of ENSO on crop production/yield between this study and previous studies

Crop	This study			Previous study						
	Country	El Niño effect(1)	La Niña effect(1)	Country /Region	El Niño effect(1)	La Niña effect(1)	ENSO Index(2)	Regression estimated(3)	Data time interval	References
Wheat	South Africa	+	(+)	South Africa	+	(+)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
Wheat	Morocco	(-)	-	Morocco	(-)	(-)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
Wheat	Spain	-	(+)	Spain	-	-	JMA	×	1961-1997	Gimeno, Ribera et al. (2002)
				Western Europe	-	N.A.	N.A.	×	1972-1993	Chen and McCarl (2000)
Wheat	United States	(+)	+	United States	(-)	(-)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				United States (Southeastern)	(-)	(+)	JMA	×	1965 - 1997	Hansen, Jones et al. (2001)
				United States	(+)/(-)	N.A.	JMA	×	1960 -1989	Izaurralde, Rosenberg et al. (1999)
Maize	Iran	(+)	+	Iran	(+)	-	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
Maize	Mexico	+	(-)	Mexico	(-)	(-)	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				Mexico	(+)/(-)	(+)/(-)	JMA	×	1960–1989	Adams, Houston et al. (2003)
Rice	Bangladesh	(-)	-	Bangladesh	(+)	(-)	SOI	×	1961-1998	Chen, McCarl et al. (2008)

Table 6.4. Continued comparison in the effect of ENSO on crop production/yield between this study and previous studies

Crop	This study			Previous study						
	Country	El Niño effect(1)	La Niña effect(1)	Country /Region	El Niño effect(1)	La Niña effect(1)	ENSO Index(2)	Regression estimated(3)	Data time interval	References
Rice	Brazil	(-)	+	Brazil	(+)	+/-	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				Brazil	(+)/(-)	(-)	SOI	×	1961-1998	Chen, McCarl et al. (2008)
Rice	Indonesia	(-)	+	Indonesia	(+)/(-)	+/-	ONI	×	1982-2006	Iizumi, Luo et al. (2014)
				Indonesia	-	+	SSTA Niño3.4	✓	1983-2001	Falcon, Naylor et al. (2004)
				Indonesia	(-)	(-)	SOI	×	1961-1998	Chen, McCarl et al. (2008)
Rice	Korea DRP	(-)	-	Korea DRP	(-)	(-)	SOI	×	1961-1998	Chen, McCarl et al. (2008)
Rice	Philippines	-	(-)	Philippines (Luzon)	(-)	(+)	SSTA Niño3.4	✓	1961–2005	Roberts, Dawe et al. (2009)
				Philippines	(-)	(-)	SOI	×	1961-1998	Chen, McCarl et al. (2008)
Rice	Vietnam	+	(+)	Vietnam	(-)	(+)	SOI	×	1961-1998	Chen, McCarl et al. (2008)

(1) “(+)” and “(-)” indicate the significant positive and negative impacts on production/yield, respectively. “+” “-’’ indicates insignificant positive and negative impact on production/yield, respectively. “(+)/ (-)” and “+/-“indicates both significant positive and negative impact and both insignificant positive and negative impact. ”N.A.” indicates the data are not available from references.

(2) ONI: Oceanic Niño Index; SOI: Sothern Oscillation Index; JMA: Japan Meteorological Agency; SSTA Niño3.4/ Niño3: Sea Surface Temperature Anomalies in Niño3.4/ Niño3 region.

(3) A regression-based framework to directly estimate the ENSO impact on crop production.

6.2 Policy Recommendations

The world population reach 9 billion people by 2050 (Lang and Heasman 2015). Several studies have suggested that, to meet global food demand, agricultural production will need to approximately double by 2050 (Pingali 2007, OECD/FAO 2012). This doubling of production will require a 2.2 percent rate of crop production growth annually, including an additional one billion tonnes of cereals per year by 2050 (Bruinsma 2009). Consequently, the agricultural sector will be challenged to ensure future food security. Despite huge advance in the technology and crop yield potential, food production still remains greatly dependent on climatic factors (Rosenzweig, Iglesias et al. 2001). Some regions may benefit from a shift in climate, others suffer from food supplied reduction, hence, there is a potential for an increase in food deprivation.

This study assumes that farmers, especially in the developing world either have very limited information about the ENSO effect, or very limited resources/opportunities to act upon the ENSO news. Appropriate national (or regional) policy responses will depend on the magnitude of crop production variability resulting from ENSO impacts, the capacity of grain storages, and whether the country is a cereal exporter or importer. Linking the potential capability of ENSO forecasts with lead times of up to 2 years (Luo, Masson et al. 2008) with understanding of the ENSO impact on cereal production is a key advancement for food management. Decision-makers (governments, companies, or individuals) may provide preparations earlier instead of expecting for initial effects to happen (Magalhaes 2000). Avoiding (or minimising) negative ENSO effects, or taking advantage of positive ENSO impacts, may be achieved by making decisions for any given crop about choices of planting and harvesting date, increased inputs of seeds, fertiliser, and pest control and irrigation (Weiher 1999, Sivakumar and Meinke 2007). Incorporating ENSO forecasts into planting decisions in the United States could enhance agricultural output and generate benefits of US$323 million for the U.S. economy, annually (Solow, Adams et al. 1998). In addition, understanding the different and conflicting ENSO impacts on various crops (for instance, in Argentina, El Niño positively impacts on wheat and rice, and negatively impacts on maize) is a beneficial tool to implement crop switching strategies. This understanding enables farmers to choose the crop that is most suited to the expected temperature and rainfall conditions, to mitigate ENSO damage and ensure food availability. Crop insurance policies, based on ENSO indices, could cut down the financial losses of ENSO-induced production reduction in order to manage risks for smallholder agriculture. Also, adaption policies such as increasing storage capacity and reducing trade barriers could mitigate ENSO damage to the international markets. Chen, McCarl et al. (2008) find that ENSO damage on international rice market partially offset by government mitigation strategies to smooth out price fluctuations. They show that both aforementioned policies enhance total social welfare; however lowering import tariffs is more effective than expanding storage capacity.

Findings of this study provide advantageous tool for global trade. When producers are able to adapt to the prospect of expected production variability, ENSO impact could be attenuated. Our results could help producers around the world to be aware of the supply variability and be able to anticipate the price variability. This enables producers to be predictive to respond early. When food-producing countries including importers and exporters could effectively respond to ENSO-induced production variability by regional trade management or stock management the risk of the global food crisis will attenuate.

Chapter 7. Conclusions

The El Niño Southern Oscillation (ENSO) is associated with weather anomalies in different parts of the world. Consequently, ENSO-related unfavourable weather conditions are likely to substantially impact agricultural production. This, in turn, causes considerable socio-economic implications in various parts of the world. An accurate understanding of the ENSO-economy relationship is important to elucidate how future weather shocks will affect agricultural activity. Then, outline effective macroeconomic policies to mitigate the adverse impacts or benefits the positive effects.

This study identifies the relationship between ENSO and world production of major cereal crops, first in the main producing countries, then on a global scale. This study uses the country-level annual crop production and ENSO data spanning 1962-2009. An understanding of how ENSO events affect food supply in the world is essential to assess the advantage of alternative adaption strategies to effectively manage food policies.

Previous approaches primarily focus on specific region or country to estimate the ENSO impact on cereal production. This study contributes to the ENSO-economy literature by incorporating the most possible extended geographical peculiarities to measure the ENSO effect on cereal production. In addition, it applies a threshold regression framework to address the potentially asymmetric nature of the ENSO shocks in production responses. Within this framework, it also incorporates an economic variable (i.e., lagged price as a proxy of expected price) to control for economic factors affecting supply. Furthermore, it controls weather-ENSO interactions by incorporating country-level growing-season average of air temperature and precipitation. Therefore, it measures the net effect of ENSO on cereal production after removing climatic effect.

Results indicate that ENSO affects many major cereal producers, as well as exporters. Our analyses of ENSO records show that the El Niño effect on cereal production, while typically negative, is indeed positive in many regions. In addition, the simultaneity of the ENSO impact in various parts of the world (i.e. spatial correlation of the ENSO-induced production variability) is apparent. Consistent with prior research, the results reveal that ENSO affects wheat, maize and rice production significantly in many parts of the world, particularly Western Pacific regional countries, and Central and South America's western coastal regions. The results show the evidence of a statistically significant relationship between ENSO events and individual production responses of countries compromising 34 percent of global wheat production, 17 percent and 26 percent of global maize and rice production, respectively.

Besides country-level ENSO effects, this study investigates the global cereal production responses to ENSO. Findings also point out the importance of ENSO to global cereal production. El Niño and La Niña events, both, reduce global cereal production. The asymmetries in responses are evident for wheat and rice. Global wheat production increases during El Niño events, but global rice production decreases. Global maize production reduces under both ENSO phases.

Our results greatly complement previous studies, and have implications for researchers and policy makers in several disciplines, including global production, commodity storage, trade, food management, spatial price stabilisation, and civil unrest. The results are beneficial for import-dependent countries to manage national trade and storage capacity on the basis of the ENSO phase presence. An effective response to ENSO could improve food availability and reduce the risk of undernourishment.

References:

Acosta-Jamett, G., et al. (2015). "El Niño Southern Oscillation drives conflict between wild carnivores and livestock farmers in a semiarid area in Chile." Journal of Arid Environments **30**: 1e5.

Adams, R. M., et al. (1999). "The economic consequences of ENSO events for agriculture." Climate Research **13**(3): 165-172.

Adams, R. M., et al. (2003). "The benefits to Mexican agriculture of an El Niño-southern oscillation (ENSO) early warning system." Agricultural and Forest Meteorology **115**(3): 183-194.

Agricultural Market Information System (AMIS) (2012). "AMIS Crop Calendar." from http://www.amis-outlook.org/fileadmin/user_upload/amis/docs/Crop_Calendar/121206-AMIS-online-crop-calendar_REDUCED3.pdf. (accessed September 2015).

Aguilar, A. and M. Vicarelli (2011). "El Nino and Mexican children: medium-term effects of early-life weather shocks on cognitive and health outcomes." Cambridge, United States: Harvard University, Department of Economics. Manuscript.

Ahrens, C. D. (2012). Meteorology today: an introduction to weather, climate, and the environment, Cengage Learning.

Akanda, A. I. (2011). "Rethinking crop diversification under changing climate, hydrology and food habit in Bangladesh." Journal of Agriculture and Environment for International Development **104**(1/2): 3-23.

Allan, R., et al. (1996). "El Nino: Southern oscillation and climatic variability."

Allan, R. J. (2000). "ENSO and climatic variability in the past 150 years." ENSO: Multiscale Variability and Global and Regional Impacts: 3-55.

Amien, I., et al. (1996). "Effects of interannual climate variability and climate change on rice yield in Java, Indonesia." Water, Air, and Soil Pollution **92**(1-2): 29-39.

Amissah-Arthur, A., et al. (2002). "Spatio-temporal effects of El Niño events on rainfall and maize yield in Kenya." International Journal of Climatology **22**(15): 1849-1860.

An, S.-I. (2009). "A review of interdecadal changes in the nonlinearity of the El Nino-Southern Oscillation." Theoretical and applied climatology **97**(1-2): 29-40.

An, S.-I. and F.-F. Jin (2001). "Collective role of thermocline and zonal advective feedbacks in the ENSO mode*." Journal of Climate **14**(16): 3421-3432.

An, S.-I. and I.-S. Kang (2000). "A further investigation of the recharge oscillator paradigm for ENSO using a simple coupled model with the zonal mean and eddy separated." Journal of Climate **13**(11): 1987-1993.

Anderson, T. W. and J. Finn (2012). The new statistical analysis of data, Springer Science & Business Media.

Asian Development Bank (2009). The Economics of Climate Change in Southeast Asia: A Regional Review.

Ati, O. F., et al. (2010). "Effects of El Nino/Southern Oscillation (ENSO) on rainfall characteristics in Katsina, Nigeria." African Journal of Agricultural Research **5**(23): 3273-3278.

Australian Bureau of Meteorology. "Climate Glossary -Southern Oscillation Index." from http://www.bom.gov.au/climate/glossary/soi.shtml.

Australian Bureau of Meteorology (2012). "Record-breaking La Niña events." from http://www.bom.gov.au/climate/enso/history/ln-2010-12/three-phases-of-ENSO.shtml.

Bagci, S., et al. (2007). "Effects of Zinc Deficiency and Drought on Grain Yield of Field-grown Wheat Cultivars in Central Anatolia." Journal of Agronomy and Crop Science **193**(3): 198-206.

Bamston, A. G., et al. (1997). "Documentation of a highly ENSO-related sst region in the equatorial pacific: Research note." Atmosphere-ocean **35**(3): 367-383.

Bannayan, M., et al. (2011). "Effects of precipitation and temperature on crop production variability in northeast Iran." International journal of Biometeorology **55**(3): 387-401.

Barlow, M., et al. (2001). "ENSO, Pacific decadal variability, and US summertime precipitation, drought, and stream flow." Journal of Climate **14**(9): 2105-2128.

Barton, S. B. and J. A. Ram ı´ rez (2004). "Effects of El Niño southern oscillation and Pacific interdecadal oscillation on water supply in the Columbia River basin." Journal of water resources planning and management **130**(4): 281-289.

Bayer, A. M., et al. (2014). "An unforgettable event: a qualitative study of the 1997–98 El Nino in northern Peru." Disasters **38**(2): 351-374.

Bellemare, M. F. (2015). "Rising food prices, food price volatility, and social unrest." American Journal of Agricultural Economics **97**(1): 1-21.

Berlato, M. A., et al. (2005). "Association between El Nino southern oscillation and corn yield in Rio Grande do Sul State." Pesquisa Agropecuária Brasileira **40**(5): 423-432.

Berry, B. J. and A. Okulicz-Kozaryn (2008). "Are there ENSO signals in the macroeconomy?" Ecological Economics **64**(3): 625-633.

Bjerknes, J. (1966). "A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature." Tellus **18**(4): 820-829.

Bjerknes, J. (1969). "Atmospheric teleconnections from the equatorial pacific 1." Monthly weather review **97**(3): 163-172.

Bouma, M., et al. (1997). "Global assessment of El Niño's disaster burden." The Lancet **350**(9089): 1435-1438.

Bove, M. C., et al. (1998). "Effect of El Niño on US landfalling hurricanes, revisited." Bulletin of the American Meteorological Society **79**(11): 2477-2482.

Broad, K. and S. Agrawala (2000). "The Ethiopia food crisis--uses and limits of climate forecasts." Science **289**(5485): 1693-1694.

Bromokusumo, A. K. and S. Meylinah (2009). El Nino Forecast for Indonesia. USDA/FAS, Washington, DC, GAIN Report ID9036.

Brönnimann, S., et al. (2007). "ENSO influence on Europe during the last centuries." Climate Dynamics **28**(2-3): 181-197.

Bruinsma, J. (2009). The resource outlook to 2050. Expert meeting on how to feed the world in.

Brunner, A. D. (2002). "El Nino and world primary commodity prices: warm water or hot air?" Review of Economics and statistics **84**(1): 176-183.

Cai, W. and T. Cowan (2009). "La Niña Modoki impacts Australia autumn rainfall variability." Geophysical Research Letters **36**(12).

Cai, W., et al. (2011). "Teleconnection pathways of ENSO and the IOD and the mechanisms for impacts on Australian rainfall." Journal of Climate **24**(15): 3910-3923.

Camberlin, P., et al. (2001). "Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO." International Journal of Climatology **21**(8): 973-1005.

Cane, M. A., et al. (1994). "Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature."

Cane, M. A., et al. (1986). "Experimental forecasts of EL Nino." Nature **321**(6073): 827-832.

CARE (1998). El Niño in 1997-1998: Impacts and CARE's Response.

Cashin, P., et al. (2014). Fair weather or foul? The macroeconomic effects of El Niño, Faculty of Economics, University of Cambridge.

Cashin, P. A., et al. (2015). "Fair weather or foul? the macroeconomic effects of El Niño."

Cavledes, C. N. (1985). "Emergency and institutional crisis in Peru during El Niño 1982–1983." Disasters **9**(1): 70-74.

Changnon, S. A. (1999). "Impacts of 1997-98 El Niño generated weather in the United States." Bulletin of the American Meteorological Society **80**(9): 1819-1827.

Changnon, S. A. (2000). El Nino 1997-1998 : The Climate Event of the Century, Oxford University Press, Inc, USA.

Chen, C.-C., et al. (2002). "Agricultural value of ENSO information under alternative phase definition." Climatic Change **54**(3): 305-325.

Chen, C.-C. and B. A. McCarl (2000). "The value of ENSO information to agriculture: consideration of event strength and trade." Journal of Agricultural and Resource Economics: 368-385.

Chen, C.-C., et al. (2001). "Economic implications of potential ENSO frequency and strength shifts." Climatic Change **49**(1-2): 147-159.

Chen, C.-C., et al. (2008). "Strong El Nino-Southern Oscillation events and the economics of the international rice market."

Chiew, F. H. S., et al. (1998). "El Nino/Southern Oscillation and Australian rainfall, streamflow and drought: Links and potential for forecasting." Journal of Hydrology **204**(1–4): 138-149.

Chimeli, A. B., et al. (2008). "Forecasting the impacts of climate variability: lessons from the rainfed corn market in Ceará, Brazil." Environment and Development Economics **13**(02): 201-227.

Coles, P. (1999). "All eyes on El Nino." The Unesco Courier **52**(5): 30.

Collins, K. J. (2007). How El Nino affects energy consumption: a study at national and regional levels, Texas A&M University.

Collins, M. (2000). "Understanding uncertainties in the response of ENSO to greenhouse warming." Geophysical Research Letters **27**(21): 3509-3512.

Dai, A. and T. Wigley (2000). "Global patterns of ENSO-induced precipitation." Geophysical Research Letters **27**(9): 1283-1286.

Danysh, H. E., et al. (2014). "El Niño adversely affected childhood stature and lean mass in northern Peru." Climate Change Responses **1**(1): 7.

Das, H. and C. Stigter (2010). Problems and solutions in using of and coping with weather phenomena in need of tactical decision making and challenges remaining for the use of science to contribute to problem analyses and designing viable solutions in this context: monocropping. Applied Agrometeorology, Springer**:** 377-383.

Dawe, D. (2012). The Rice Crisis:" Markets, Policies and Food Security", Routledge.

Dawe, D., et al. (2009). "Institutional, policy and farmer responses to drought: El Niño events and rice in the Philippines." Disasters **33**(2): 291-307.

DeLong, R. L. and G. A. Antonelis (1991). Impact of the 1982–1983 El Niño on the northern fur seal population at San Miguel Island, California. Pinnipeds and El Niño, Springer**:** 75-83.

Deng, X., et al. (2010). "Impacts of El Nino-Southern Oscillation events on China's rice production." Journal of Geographical Sciences **20**(1): 3-16.

Deng, X., et al. (2010). "Impacts of El Nino-Southern Oscillation events on China’s rice production." Journal of Geographical Sciences **20**(1): 3-16.

Diaz, A. F., et al. (1998). "Relationships between precipitation anomalies in Uruguay and southern Brazil and sea surface temperature in the Pacific and Atlantic Oceans." Journal of Climate **11**(2): 251-271.

Dilley, M. and B. N. Heyman (1995). "ENSO and disaster: droughts, floods and El Nino/Southern Oscillation warm events." Disasters **19**(3): 181-193.

Du Toit, A. S. and M. A. Prinsloo (2001). "El Niño-southern oscillation effects on maize production in South Africa: A preliminary methodology study." Impacts of El Niño and climate variability on agriculture(impactsofelnino): 77-86.

Ellis, F. (1993). "Private trade and public role in staple food marketing: the case of rice in Indonesia." Food Policy **18**(5): 428-438.

Eltahir, E. A. (1996). "El Niño and the natural variability in the flow of the Nile River." Water Resources Research **32**(1): 131-137.

Falcon, W. P., et al. (2004). "Using climate models to improve Indonesian food security." Bulletin of Indonesian Economic Studies **40**(3): 355-377.

FAO (2007). T STATE OF FOOD AND AGRICULTURE;PAYING FARMERS FOR ENVIRONMENTAL SERVICES. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome

FAO (2014). Ethiopia: El Niño-Southern Oscillation (ENSO) and the main Kiremt rainy season

Fedorov, A., et al. (2003). "How predictable is El Niño?" Bulletin of the American Meteorological Society **84**(7): 911-919.

Fedorov, A. V. and S. G. Philander (2000). "Is El Niño changing?" Science **288**(5473): 1997-2002.

Feng, H. and B. A. Babcock (2010). "Impacts of ethanol on planted acreage in market equilibrium." American Journal of Agricultural Economics **92**(3): 789-802.

Fraedrich, K. (1994). "An ENSO impact on Europe?" Tellus A **46**(4): 541-552.

Garcia, A., et al. (2003). "Effects of 1997–1998 El Niño on the dynamics of the shallow-water fish assemblage of the Patos Lagoon Estuary (Brazil)." Estuarine, coastal and shelf Science **57**(3): 489-500.

Garnett, E. R. and M. L. Khandekar (1992). "The impact of large-scale atmospheric circulations and anomalies on Indian monsoon droughts and floods and on world grain yields—a statistical analysis." Agricultural and Forest Meteorology **61**(1): 113-128.

Gates, W. E. (1967). "The spread of Ibn Khaldun's ideas on climate and culture." Journal of the History of Ideas: 415-422.

Gergis, J. L. and A. M. Fowler (2009). "A history of ENSO events since AD 1525: implications for future climate change." Climatic Change **92**(3-4): 343-387.

Gimeno, L., et al. (2002). "Identification of empirical relationships between indices of ENSO and NAO and agricultural yields in Spain." Climate Research **21**(2): 165-173.

Glantz, M. H. (2001). Currents of change: impacts of El Niño and La Niña on climate and society, Cambridge University Press.

Global Information and Early Warning System on food and agriculture (GIEWS) (2014). "GIEWS Country Briefs." from http://www.fao.org/giews/countrybrief/. (accessed September 2015). .

Goddard, L. and M. Dilley (2005). "El Nino: catastrophe or opportunity." Journal of Climate **18**(5): 651-665.

Gommes, R., et al. (1998). Climate impact on agriculture, An El Nino primer. Rome, Food and Agriculture Organization of the United Nations,.

Green, P., et al. (1997). "The North American Climate Patterns Associated with El Niño-Southern Oscillation. Report 97-1." Center for Ocean-Atmospheric Prediction Studies, Tallahassee, FL **32306**: 17.

Grimm, A. M., et al. (1998). "Precipitation anomalies in southern Brazil associated with El Niño and La Niña events." Journal of Climate **11**(11): 2863-2880.

Hachigonta, S. and C. Reason (2006). "Interannual variability in dry and wet spell characteristics over Zambia." Climate Research **32**(1): 49.

Halpert, M. S. and C. F. Ropelewski (1992). "Surface temperature patterns associated with the Southern Oscillation." Journal of Climate **5**(6): 577-593.

Hammer, G., et al. (2001). "Advances in application of climate prediction in agriculture." Agricultural Systems **70**(2): 515-553.

Handler, A. (1990). "USA corn yields, the El Niñmo and agricultural drought: 1867–1988." International Journal of Climatology **10**(8): 819-828.

Handler, P. (1984). "Corn yields in the United States and sea surface temperature anomalies in the equatorial Pacific Ocean during the period 1868–1982." Agricultural and Forest Meteorology **31**(1): 25-32.

Hanley, D. E., et al. (2003). "A quantitative evaluation of ENSO indices." Journal of Climate **16**(8): 1249-1258.

Hansen, J., et al. (2001). "El Niño-southern oscillation impacts on crop production in the southeast United States." Impacts of El Niño and climate variability on agriculture(impactsofelnino): 55-76.

Hansen, J. W., et al. (1998). "ENSO influences on agriculture in the southeastern United States." Journal of Climate **11**(3).

Hansen, J. W., et al. (1999). "El Niño-Southern Oscillation Impacts on Winter Vegetable Production in Florida*." Journal of Climate **12**(1): 92-102.

Harger, J. (1995). "Air-temperature variations and ENSO effects in Indonesia, the Philippines and El Salvador. ENSO patterns and changes from 1866–1993." Atmospheric Environment **29**(16): 1919-1942.

Harris, S., et al. (2014). "Corrigendum to: Forecasting fire activity in Victoria, Australia, using antecedent climate variables and ENSO indices." International journal of wildland fire **23**(2): 290-293.

Harrison, M. and C. F. Meindl (2001). "A statistical relationship between El Nino-Southern Oscillation and Florida wildfire occurrence." Physical Geography **22**(3): 187-203.

Hayes, S., et al. (1991). "TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean." Bulletin of the American Meteorological Society **72**(3): 339-347.

Hicks, D. L. and B. Maldonado (2015). "Climate Change and Civil Unrest: Evidence from the El Niño Southern Oscillation." Available at SSRN.

Hilario, F., et al. (2009). "El Niño southern oscillation in the Philippines: impacts, forecasts, and risk managements." Philippine J. Dev **36**: 9-34.

Hill, H. S., et al. (2001). "Effects of seasonal climate variability and the use of climate forecasts on wheat supply in the United States, Australia, and Canada." Impacts of El Niño and climate variability on agriculture(impactsofelnino): 101-123.

Holland, G. J. (1986). "Interannual variability of the Australian summer monsoon at Darwin: 1952-82." Monthly weather review **114**(3): 594-604.

Holton, J. R., et al. (1989). El Niño, La Niña, and the southern oscillation. San Diego,California, Academic press, Inc.

Hossain, E., et al. (2000). The Assessment of El Nino Impacts and Responses: Strategies for the 1997-98 El Nino Event in Bangladesh, Bangladesh Public Administration Training Centre.

Hsiang, S. M. and M. Burke (2014). "Climate, conflict, and social stability: what does the evidence say?" Climatic Change **123**(1): 39-55.

Hsiang, S. M. and K. C. Meng (2015). "Tropical Economics." American Economic Review **105**(5): 257-261.

Hsiang, S. M., et al. (2011). "Civil conflicts are associated with the global climate." Nature **476**(7361): 438-441.

Hu, Z. Z., et al. (2005). "Connection of summer rainfall variations in South and East Asia: role of El Niño–southern oscillation." International Journal of Climatology **25**(9): 1279-1289.

Hurrell, J. W. and H. Van Loon (1997). Decadal variations in climate associated with the North Atlantic Oscillation. Climatic Change at High Elevation Sites, Springer**:** 69-94.

Iizumi, T., et al. (2014). "Impacts of El Niño Southern Oscillation on the global yields of major crops." Nature communications **5**.

Indeje, M., et al. (2000). "ENSO signals in East African rainfall seasons." International Journal of Climatology **20**(1): 19-46.

Ineson, S. and A. Scaife (2009). "The role of the stratosphere in the European climate response to El Niño." Nature Geoscience **2**(1): 32-36.

Ingram, J. C. and T. P. Dawson (2005). "Climate change impacts and vegetation response on the island of Madagascar." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **363**(1826): 55-59.

Irawan, B. (2002). Stabilization of Upland Agriculture Under El Nino-Induced Climatic Risk: Impact Assessment and Mitigation Measures in Indonesia.

IRI (a), I. R. I. f. c. a. S. "ENSO Impacts." Retrieved 6/05/2015, from http://iridl.ldeo.columbia.edu/maproom/ENSO/Impacts.html.

IRI (b), I. R. I. f. c. a. S. "What is ENSO? Walker: Identifying the Southern Oscillation." Retrieved 12/05/2015, from http://iridl.ldeo.columbia.edu/maproom/ENSO/New/walker.html.

IRI, I. R. I. f. c. a. S. (2015b). "ENSO Essentials." Retrieved 18/05/2015, from http://iri.columbia.edu/our-expertise/climate/enso/enso-essentials/.

Izaurralde, R., et al. (1999). "Modeled effects of moderate and strongLos Niños' on crop productivity in North America." Agricultural and Forest Meteorology **94**(3): 259-268.

Janowiak, J. E. (1988). "An investigation of interannual rainfall variability in Africa." Journal of Climate **1**(3): 240-255.

Jintrawet, A. and C. Buddhaboon (2011). El Nino–Southern oscillation and rice production in Thailand during 1980–2002 period. International conference on the role of agriculture and natural resources on global changes (ANGC2011), Chiang Mai.

Johnson, S. L. (1988). "The effects of the 1983 El Nino on Oregon's coho (Oncorhynchus kisutch) and chinook (O. tshawytscha) salmon." Fisheries Research **6**(2): 105-123.

Joly, M. and A. Voldoire (2009). "Influence of ENSO on the West African monsoon: temporal aspects and atmospheric processes." Journal of Climate **22**(12): 3193-3210.

Jones, J. W., et al. (2000). "Potential benefits of climate forecasting to agriculture." Agriculture, Ecosystems & Environment **82**(1): 169-184.

Kahya, E. and J. A. Dracup (1993). "US streamflow patterns in relation to the El Niño/Southern Oscillation." Water Resources Research **29**(8): 2491-2503.

Kandji, S., et al. (2006). Climate Change Climate and Variability in Southern Africa: Impacts and Adaptation in the Agricultural Sector United Nations Environmental Programme and World Agroforestry Centre.[Links]**:** 36.

Kane, R. (1998). "ENSO relationship to the rainfall of Sri Lanka." International Journal of Climatology **18**(8): 859-871.

Karanja, F., et al. (2000). "Reducing The Impacts Of Environmental Emergencies Through Early Warning And Preparedness, The Case Of El-Nino-Southern Oscillation (ENSO)."

Kaufmann, R. K. and S. E. Snell (1997). "A biophysical model of corn yield: integrating climatic and social determinants." American Journal of Agricultural Economics **79**(1): 178-190.

Keppenne, C. L. (1995). "An ENSO signal in soybean futures prices." Journal of Climate **8**(6): 1685-1689.

Khandekar, M. L. (1996). El Niño/southern oscillation, Indian monsoon and world grain yields—a synthesis. Land-Based and Marine Hazards, Springer**:** 79-95.

Kiladis, G. N. and H. F. Diaz (1989). "Global climatic anomalies associated with extremes in the Southern Oscillation." Journal of Climate **2**(9): 1069-1090.

Kinter III, J., et al. (2002). "Recent change in the connection from the Asian monsoon to ENSO." Journal of Climate **15**(10): 1203-1215.

Kitzberger, T., et al. (2001). "Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation." Global Ecology and Biogeography **10**(3): 315-326.

Klein, S. A., et al. (1999). "Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge." Journal of Climate **12**(4): 917-932.

Korecha, D. and A. G. Barnston (2007). "predictability of June-September rainfall in Ethiopia." Monthly weather review **135**(2): 628-650.

Koutavas , A. (2011). A Brief History of El Niño:Last 25,000 Years. National Oceanic and Atmospheric Administration, College of Staten Island and Graduate Center City University of New York.

Kovats, R. S. (2000). "El Niño and human health." Bulletin of the World Health Organization **78**(9): 1127-1135.

Kovats, R. S., et al. (2003). "El Niño and health." The Lancet **362**(9394): 1481-1489.

Krishna Kumar, K., et al. (2004). "Climate impacts on Indian agriculture." International Journal of Climatology **24**(11): 1375-1393.

Kruger, A. (1999). "The influence of the decadal-scale variability of summer rainfall on the impact of El Niño and La Niña events in South Africa." International Journal of Climatology **19**(1): 59-68.

Kumar, K. K., et al. (1999). "On the weakening relationship between the Indian monsoon and ENSO." Science **284**(5423): 2156-2159.

Lang, T. and M. Heasman (2015). Food wars: The global battle for mouths, minds and markets, Routledge.

Lansigan, F., et al. (2000). "Agronomic impacts of climate variability on rice production in the Philippines." Agriculture, Ecosystems & Environment **82**(1): 129-137.

Lansigan, F. P. (2005). Coping with climate variability and change in rice production systems in the Philippines. Rice is Life: Scientific Perspectives for the 21st Century: Proceedings of the World Rice Research Conference, International Rice Research Institute.

Latif, M., et al. (1998). "A review of the predictability and prediction of ENSO." Journal of Geophysical Research: Oceans (1978–2012) **103**(C7): 14375-14393.

Lau, K. and H. Weng (2001). "Coherent modes of global SST and summer rainfall over China: An assessment of the regional impacts of the 1997-98 El Nino." Journal of Climate **14**(6): 1294-1308.

Lee, M.-L. T., et al. (2010). Benefits of threshold regression: a case-study comparison with Cox proportional hazards regression. Mathematical and Statistical Models and Methods in Reliability, Springer**:** 359-370.

Legler, D. M., et al. (1999). "Impact of ENSO-related climate anomalies on crop yields in the US." Climatic Change **42**(2): 351-375.

Letson, D. and B. McCullough (2001). "ENSO and soybean prices: Correlation without causality." Journal of Agricultural and Applied Economics **33**(3): 513-522.

Liu, Y., et al. (2014). "Climate and crop yields impacted by ENSO episodes on the North China Plain: 1956–2006." Regional Environmental Change **14**(1): 49-59.

Lobell, D. B. and M. B. Burke (2008). "Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation." Environmental Research Letters **3**(3): 034007.

Lobell, M. J. (1942). "Some observations on the Peruvian coastal current." Eos, Transactions American Geophysical Union **23**(2): 332-336.

Lockyer, N. and W. J. Lockyer (1902a). "On some phenomena which suggest a short period of solar and meterological changes." Proceedings of the Royal Society of London **70**(459-466): 500-504.

Lockyer, N. and W. J. Lockyer (1902b). "On the similarity of the short-period pressure variation over large areas." Proceedings of the Royal Society of London **71**(467-476): 134-135.

Lockyer, N. and W. J. Lockyer (1904). "The behaviour of the short-period atmospheric pressure variation over the earth's surface." Proceedings of the Royal Society of London: 457-470.

Luo, J.-J., et al. (2008). "Extended ENSO predictions using a fully coupled ocean-atmosphere model." Journal of Climate **21**(1): 84-93.

Luo, Q. (2011). "Temperature thresholds and crop production: a review." Climatic Change **109**(3-4): 583-598.

Lyon, B. and A. G. Barnston (2005). "ENSO and the spatial extent of interannual precipitation extremes in tropical land areas." Journal of Climate **18**(23): 5095-5109.

Lyon, B. and A. G. Barnston (2005). "The evolution of the weak El Niño of 2004–2005." US CLIVAR Variations **3**(2): 1-4.

Maclean, J., et al. (2013). Rice Almanac: Source Book for One of the Most Important Economic Activities on Earth, IRRI.

Magalhaes, A. (2000). Sustainable development: climate and policy linkages. Proc Int Forum Clim Predict, Agric Dev.

Mahmood, A., et al. (2004). "Correlation between Multivariate ENSO Index (MEI) and Pakistan’s summer rainfall." Pakistan Journal of Meteorology Vol **1**(2).

Mariotti, A., et al. (2002). "Euro-Mediterranean rainfall and ENSO—a seasonally varying relationship." Geophysical Research Letters **29**(12): 59-51-59-54.

Martinez, C. J., et al. (2009). "Use of climate indices to predict corn yields in southeast USA." International Journal of Climatology **29**(11): 1680-1691.

Mason, S. and P. Tyson (2000). "The occurrence and predictability of droughts over southern Africa." Drought: a global assessment: 113-134.

Mason, S. J. (2001). "El Niño, climate change, and Southern African climate." Environmetrics **12**(4): 327-345.

Mason, S. J. and L. Goddard (2001). "Probabilistic precipitation anomalies associated with ENSO." Bulletin of the American Meteorological Society **82**(4): 619-638.

Mason, S. J., et al. (1999). "The IRI seasonal climate prediction system and the 1997/98 El Niño event." Bulletin of the American Meteorological Society **80**(9): 1853-1873.

McPhaden, M. J. (1999). "Genesis and evolution of the 1997-98 El Niño." Science **283**(5404): 950-954.

McPhaden, M. J., et al. (1998). "The Tropical Ocean-Global Atmosphere observing system: A decade of progress." Journal of Geophysical Research: Oceans (1978–2012) **103**(C7): 14169-14240.

McPhaden, M. J., et al. (2006). "ENSO as an integrating concept in earth science." Science **314**(5806): 1740-1745.

Mears, L. A. (1981). "The new rice economy of Indonesia." The new rice economy of Indonesia.

Meinke, H. and R. Stone (1997). "On tactical crop management using seasonal climate forecasts and simulation modelling: a case study for wheat." Scientia Agricola **54**(SPE): 121-129.

Merkel, U. and M. Latif (2002). "A high resolution AGCM study of the El Nino impact on the North Atlantic/European sector." Geophysical Research Letters **29**(9): 5-1-5-4.

Messina, C., et al. (1999). "Land allocation conditioned on El Niño-Southern Oscillation phases in the Pampas of Argentina." Agricultural Systems **60**(3): 197-212.

Meyers, S., et al. (1999). "Reconstruction of Monthly SST in the Tropical Pacific Ocean during 1868-1993Using Adaptive Climate Basis Functions." Monthly weather review **127**(7): 1599-1612.

Miao, R., et al. (2016). "Responsiveness of crop yield and acreage to prices and climate." American Journal of Agricultural Economics **98**(1): 191-211.

Mjelde, J. W., et al. (1998). "A review of current evidence on climate forecasts and their economic effects in agriculture." American Journal of Agricultural Economics: 1089-1095.

Mo, K. C. and J. E. Schemm (2008). "Relationships between ENSO and drought over the southeastern United States." Geophysical Research Letters **35**(15).

Montroy, D. L., et al. (1998). "Observed nonlinearities of monthly teleconnections between tropical Pacific sea surface temperature anomalies and central and eastern North American precipitation." Journal of Climate **11**(7): 1812-1835.

Moradi, R., et al. (2014). "Adaptation of maize to climate change impacts in Iran." Mitigation and Adaptation Strategies for Global Change **19**(8): 1223-1238.

National weather service Climate Prediction Centre (2014). "Monthly ERSST.V3B (1981-2010 base period) Niño 1+2 (0-10°South)(90°West-80°West) Niño 3 (5°North-5°South)(150°West-90°West) Niño 4 (5°North-5°South) (160°East-150°West) Niño 3.4 (5°North-5°South)(170-120°West)." from http://www.cpc.ncep.noaa.gov/data/indices. (accessed April 2014).

Naylor, R., et al. (2002). "Using El Nino-Southern Oscillation climate data to improve food policy planning in Indonesia." Bulletin of Indonesian Economic Studies **38**(1): 75-91.

Naylor, R., et al. (2002). "Using El Niño-Southern Oscillation climate data to improve food policy planning in Indonesia." Bulletin of Indonesian Economic Studies **38**(1): 75-91.

Naylor, R. L., et al. (2001). "Using El Nino/Southern Oscillation climate data to predict rice production in Indonesia." Climatic Change **50**(3): 255-265.

Nazemosadat, M. and I. Cordery (2000). "On the relationships between ENSO and autumn rainfall in Iran." International Journal of Climatology **20**(1): 47-61.

Neelin, J. D., et al. (1998). "ENSO theory." Journal of Geophysical Research: Oceans (1978–2012) **103**(C7): 14261-14290.

Newey, W. K. and K. D. West (1986). A simple, positive semi-definite, heteroskedasticity and autocorrelationconsistent covariance matrix, National Bureau of Economic Research Cambridge, Mass., USA.

Nicholls, N. (1985). "Impact of the Southern Oscillation on Australian crops." Journal of Climatology **5**(5): 553-560.

Nicholls, N. (1991). The El Nino/southern oscillation and Australian vegetation. Vegetation and climate interactions in semi-arid regions, Springer**:** 23-36.

Nicholson, S. E. and J. Kim (1997). "The relationship of the El Nino-Southern oscillation to African rainfall." International Journal of Climatology **17**(2): 117-135.

NOAA (2014). "Weather Impacts of ENSO." from http://www.srh.noaa.gov/jetstream/tropics/enso_impacts.htm.

NOAA, N. O. a. A. A., National Centre for Enviromental Information. "Equatorial Pacific Sea Surface Temperatures." Retrieved 20/05/2015, from https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php.

O’Brien, J., et al. (1999). "El Niño, La Niña and Florida’s climate: effects on agriculture and forestry." The Florida Consortium: The Florida State University, University of Florida. University of Miami, Tallahassee, FL.

OECD/FAO (2012). OECD-FAO Agricultural Outlook 2012–2021, OECD Publishing and FAO Paris.

Oram, P. A. (1985). "Sensitivity of agricultural production to climatic change." Climatic Change **7**(1): 129-152.

Ortlieb, L. (2000). "The documented historical record of El Niño events in Peru: an update of the Quinn record (sixteenth through nineteenth centuries)." El Niño and the Southern Oscillation: Multiscale variability and global and regional impacts: 207-295.

Pandey, S., et al. (2007 a). "Coping with drought in rice farming in Asia: insights from a cross-country comparative study." Agricultural Economics **37**(s1): 213-224.

Pandey, S., et al. (2007b). Economic costs of drought and rice farmers' coping mechanisms: a cross-country comparative analysis, Int. Rice Res. Inst.

Park, S. (2004). "Remote ENSO influence on Mediterranean sky conditions during late summer and autumn: Evidence for a slowly evolving atmospheric bridge." Quarterly Journal of the Royal Meteorological Society **130**(602): 2409-2422.

Parthasarathy, B., et al. (1988). "Regression model for estimation of Indian foodgrain production from summer monsoon rainfall." Agricultural and Forest Meteorology **42**(2): 167-182.

Patt, A. and C. Gwata (2002). "Effective seasonal climate forecast applications: examining constraints for subsistence farmers in Zimbabwe." Global Environmental Change **12**(3): 185-195.

Paxton, K. L., et al. (2014). "El Niño-Southern Oscillation Is Linked to Decreased Energetic Condition in Long-Distance Migrants." PloS one **9**(5): e95383.

Penalba, O. C. and F. A. Robledo (2005). "Frequency of precipitation in the humid pampa of Argentina." Atlantic **40**(35): 30.

Pfaff, A., et al. (1999). "Who benefits from climate forecasts?" Nature **397**(6721): 645-646.

Philander, S. (1985). "El Niño and La Niña." Journal of the Atmospheric Sciences **42**(23): 2652-2662.

Philander, S. G. (2008). Encyclopedia of global warming and climate change, Sage Publications.

Philippon, N., et al. (2002). "Empirical predictability study of October–December East African rainfall." Quarterly Journal of the Royal Meteorological Society **128**(585): 2239-2256.

Phillips, J., et al. (1999). "The role of ENSO in determining climate and maize yield variability in the US cornbelt." International Journal of Climatology **19**(8): 877-888.

Phillips, J. G., et al. (1998). "ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe." Agricultural and Forest Meteorology **90**(1–2): 39-50.

Pierce, D. W. (2011). "El Niños of the Past." Retrieved 21/05/2015, from http://meteora.ucsd.edu/~pierce/elnino/history.html.

Pingali, P. (2007). "Westernization of Asian diets and the transformation of food systems: implications for research and policy." Food Policy **32**(3): 281-298.

Podesta, G., et al. (2002). "Use of ENSO-related climate information in agricultural decision making in Argentina: a pilot experience." Agricultural Systems **74**(3): 371-392.

Podestá, G. P., et al. (1999). "Associations between grain crop yields in central-eastern Argentina and El Niño-Southern Oscillation." Journal of Applied Meteorology **38**(10): 1488-1498.

Pol, M. and J. Binyamin (2014). "Impact of Climate Change and Variability on Wheat and Corn Production in Buenos Aires, Argentina." American Journal of Climate Change **2014**.

Pozo-Vázquez, D., et al. (2001). "The association between ENSO and winter atmospheric circulation and temperature in the North Atlantic region." Journal of Climate **14**(16): 3408-3420.

Punyawardena, B. and N. Cherry (1999). "Assessment of the predictability of seasonal rainfall in Ratnapura using the southern oscillation and its two extremes." Journal of the National Science Foundation of Sri Lanka **27**(3): 187-195.

Quinn, W. H. (1987). El NIÑOEl niño. Climatology, Springer**:** 411-414.

Raible, C. C., et al. (2004). "Precipitation and northern hemisphere regimes." Atmospheric Science Letters **5**(1-4): 43-55.

Ramage, C. S. (1986). "El Niño." Sci. Am.;(United States) **254**(6).

RAO, G. S. L. H. V. P. (2008). Agricultural Meteorology. New Delhi,India, Prentice-Hall.

Rasmusson, E. M. and T. H. Carpenter (1982). "Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño." Monthly weather review **110**(5): 354-384.

Rasmusson, E. M. and T. H. Carpenter (1983). "The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka." Monthly weather review **111**(3): 517-528.

Rasmusson, E. M. and J. M. Wallace (1983). "Meteorological aspects of the El Nino/southern oscillation." Science **222**(4629): 1195-1202.

Reynolds, M. P. (2010). Climate change and crop production. Cambridge, MA; Wallingford, Oxfordshire, UK, CABI.

Rimmington, G. and N. Nicholls (1993). "Forecasting wheat yields in Australia with the Southern Oscillation Index." Crop and Pasture Science **44**(4): 625-632.

Roberts, M. G., et al. (2009). "El Niño-Southern Oscillation impacts on rice production in Luzon, the Philippines." Journal of applied meteorology and climatology **48**(8): 1718-1724.

Roberts, M. G., et al. (2009). "El Niño–Southern Oscillation Impacts on Rice Production in Luzon, the Philippines." Journal of Applied Meteorology & Climatology **48**(8).

Roel, A. and W. Baethgen (2007). Towards the development of a spatial decision support system (SDSS) for the application of climate forecasts in Uruguayan rice production sector. Climate Prediction and Agriculture, Springer**:** 89-97.

Ropelewski, C. F. and M. Halpert (1989). "Precipitation patterns associated with the high index phase of the Southern Oscillation." Journal of Climate **2**(3): 268-284.

Ropelewski, C. F. and M. S. Halpert (1987). "Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation." Monthly weather review **115**(8): 1606-1626.

Ropelewski, C. F. and M. S. Halpert (1996). "Quantifying southern oscillation-precipitation relationships." Journal of Climate **9**(5): 1043-1059.

Rosenzweig, C. and D. Hillel (2008). Climate variability and the global harvest: impacts of El Niño and other oscillations on agroecosystems, Oxford University Press New York.

Rosenzweig, C., et al. (2000). Climate change and US agriculture: The impacts of warming and extreme weather events on productivity, plant diseases, and pests, Center for Health and the Global Environment, Harvard Medical School.

Rosenzweig, C., et al. (2001). "Climate change and extreme weather events; implications for food production, plant diseases, and pests." Global change & human health **2**(2): 90-104.

Rowell, D. P. (2001). "Teleconnections between the tropical Pacific and the Sahel." Quarterly Journal of the Royal Meteorological Society **127**(575): 1683-1706.

Royce, F. S., et al. (2011). "ENSO classification indices and summer crop yields in the Southeastern USA." Agricultural and Forest Meteorology **151**(7): 817-826.

Salinger, M. J. (2005). "Climate variability and change: past, present and future–an overview." Climatic Change **70**(1-2): 9-29.

Sarachik, E. S. and M. A. Cane (2010). The El Nino-southern oscillation phenomenon, Cambridge University Press.

Schlenker, W. and M. J. Roberts (2008). Estimating the impact of climate change on crop yields: The importance of nonlinear temperature effects, National Bureau of Economic Research.

Schlenker, W. and M. J. Roberts (2009). "Nonlinear temperature effects indicate severe damages to US crop yields under climate change." Proceedings of the National Academy of Sciences **106**(37): 15594-15598.

Schopf, P. S. and R. J. Burgman (2006). "A simple mechanism for ENSO residuals and asymmetry." Journal of Climate **19**(13): 3167-3179.

Selvaraju, R. (2003). "Impact of El Nino–southern oscillation on Indian foodgrain production." International Journal of Climatology **23**(2): 187-206.

Selvaraju, R. (2011). "World food security: The challenges of climate change and bioenergy." Climate change and food security in South Asia: 185-211.

Shaman, J. (2014). "The Seasonal Effects of ENSO on European Precipitation: Observational Analysis." Journal of Climate **27**(17): 6423-6438.

Shaman, J. and E. Tziperman (2011). "An atmospheric teleconnection linking ENSO and southwestern European precipitation." Journal of Climate **24**(1): 124-139.

Sheng, F. and C. Xiuling (2004). Influence of atmospheric precipitation on soil leaching and desalinization in semi-humid region. 13th International Soil Conservation Organization Conference, Conserving Soil and Water for Society: Sharing Solutions–Brisbane.

Shrestha, M. (2000). "Interannual variation of summer monsoon rainfall over Nepal and its relation to Southern Oscillation Index." Meteorology and Atmospheric Physics **75**(1-2): 21-28.

Shuai, J., et al. (2013). "ENSO, climate variability and crop yields in China." Climate Research **58**(2): 133-148.

Shuai, J., et al. (2015). "How ENSO affects maize yields in China: understanding the impact mechanisms using a process-based crop model." International Journal of Climatology.

Siegert, F. and A. A. Hoffmann (2000). "The 1998 forest fires in East Kalimantan (Indonesia): A quantitative evaluation using high resolution, multitemporal ERS-2 SAR images and NOAA-AVHRR hotspot data." Remote Sensing of Environment **72**(1): 64-77.

Siegert, F., et al. (2001). "Increased damage from fires in logged forests during droughts caused by El Nino." Nature **414**(6862): 437-440.

Sikka, D. (1980). "Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters." Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences **89**(2): 179-195.

Sivakumar, M., et al. (2005). "Impacts of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics." Climatic Change **70**(1-2): 31-72.

Sivakumar, M. V. and H. Meinke (2007). Climate prediction and agriculture, Springer.

Solow, A. R., et al. (1998). "The value of improved ENSO prediction to US agriculture." Climatic Change **39**(1): 47-60.

Sreenivas, G., et al. (2008). "Prediction of phenology in aerobic rice using agrometeorological indices." JOURNAL OF AGROMETEOROLOGY **10**: 111-114.

Stone, R. C., et al. (1996). "Prediction of global rainfall probabilities using phases of the Southern Oscillation Index."

Subbiah, A., et al. (2001). "Long-range Climate Forecasts for Agriculture and Food Security." Asian Disaster Preparedness Center. Bangkok, Thailand.

Tack, J. B. and D. Ubilava (2013). "The effect of El Niño Southern Oscillation on US corn production and downside risk." Climatic Change **121**(4): 689-700.

Takaoka, S. (2005). "Impact of the 1997-1998 El Niño Rains on Farms in the Mount Kenya Region." Mountain Research and Development **25**(4): 326-331.

Tao, F., et al. (2008). "Global warming, rice production, and water use in China: developing a probabilistic assessment." Agricultural and Forest Meteorology **148**(1): 94-110.

Tao, F., et al. (2004). "Variability in climatology and agricultural production in China in association with the East Asian summer monsoon and El Niño Southern Oscillation." Climate Research **28**(1): 23-30.

Taschetto, A. S. and M. H. England (2009). "El Niño Modoki impacts on Australian rainfall." Journal of Climate **22**(11): 3167-3174.

Temin, P. (2002). "Price behavior in ancient Babylon." Explorations in Economic History **39**(1): 46-60.

Thomson, M., et al. (2003). "El Niño and drought in southern Africa." The Lancet **361**(9355): 437-438.

Timmermann, A., et al. (1999). "Increased El Niño frequency in a climate model forced by future greenhouse warming." Nature **398**(6729): 694-697.

Todey, D., et al. (1999). ENSO and soil moisture effects on corn yields in the Midwest. Preprints of the 11th Conference on Applied Climatology, Dallas, TX. American Society of Meteorology, Boston, MA.

Tong, H. (1983). Threshold models in non-linear time series analysis, Springer Science & Business Media.

Toole, G. a. S. (2002). Essential AS Biology. Delta Place, United Kingdom, Nelson Thornes Ltd.

Trager, J. (1975). The great grain robbery, Ballantine Books.

Travasso, M. I., et al. (2003). "Relations between sea-surface temperature and crop yields in Argentina." International Journal of Climatology **23**(13): 1655-1662.

Trenberth, K. E. (1997). "The definition of el nino." Bulletin of the American Meteorological Society **78**(12): 2771-2777.

Trenberth, K. E. (1999). "The extreme weather events of 1997 and 1998." Consequences **5**(1): 3-15.

Trenberth, K. E., et al. (1998). "Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures." Journal of Geophysical Research: Oceans (1978–2012) **103**(C7): 14291-14324.

Trenberth, K. E. and T. J. Hoar (1996). "The 1990–1995 El Niño-Southern Oscillation event: Longest on record." Geophysical Research Letters **23**(1): 57-60.

Trenberth, K. E. and D. P. Stepaniak (2001). "Indices of El Niño evolution." Journal of Climate **14**(8): 1697-1701.

Ubilava, D. (2012). "El Nino, La Nina, and world coffee price dynamics." Agricultural Economics **43**(1): 17-26.

Ubilava, D. (2014). The ENSO Effect on World Wheat Market Dynamics: Smooth Transitions in Asymmetric Price Transmission. 2014 Annual Meeting, July 27-29, 2014, Minneapolis, Minnesota, Agricultural and Applied Economics Association.

Ubilava, D. and M. Holt (2013). "El Niño southern oscillation and its effects on world vegetable oil prices: assessing asymmetries using smooth transition models." Australian Journal of Agricultural and Resource Economics **57**(2): 273-297.

Ubilava, D. and M. T. Holt (2009). Nonlinearities in the world vegetable oil price system: El Nino effects. 2009 Annual Meeting, July.

US. Bureau of Labor Statistics. "Producer Price Index for All Commodities [PPIACO]." from https://research.stlouisfed.org/fred2/series/PPIACO/. (accessed September 2015).

USAID (2014). SOUTHERN AFRICA Special Report: 2014/15 El Niño Event ;Potential impacts of an El Niño event in southern Africa are likely to vary significantly, Famine Early Warning Systems Network;USAID.

Varikoden, H., et al. (2014). "Droughts of Indian summer monsoon associated with El Niño and Non-El Niño years." International Journal of Climatology.

Vedwan, N. and K. Broad (2003). "El Niño in History: Storming through the Ages." American Anthropologist **105**(2): 396-397.

Verdon, D. C., et al. (2004). "Multidecadal variability of rainfall and streamflow: Eastern Australia." Water Resources Research **40**(10).

Villoria, N. B. (2015). The Role of Variable Trade Policy and Early Warnings in Mitigating the Global Effects of El Nino Southern Oscillation. I. F. P. a. C. Teleconnections. Unpublished manuscript.

Waddington, S. R. (1993). Overview of the current situation and previous impact of adaptive agricultural research in southern Africa. ACIAR proceedings, Australian Centre for International Agricultural Research.

Walker, G. T. (1923). "Correlation in seasonal variations of weather VIII." Mem. India Meteor. Dept **24**: 75-131.

Walker, G. T. (1924). " Correlation in seasonal variations of weather IX: A further study of world weather " Memoirs of the Royal Meteorological Society **24**(9): 275-332.

Walker, G. T. and E. W. Bliss (1932). "World Weather V." Memoirs of the Royal Meteorological Society **4**(36): 53-84.

Wallace, J. M. and S. Vogel (1994). "El Niño and Climate Prediction." Reports to the Nation on Our Changing Planet, . from http://www.pmel.noaa.gov/tao/elnino/report/credits.html.

Wang, C., et al. (2012). "El Nino-Southern Oscillation (ENSO): a review."

Wang, C. and P. C. Fiedler (2006). "ENSO variability and the eastern tropical Pacific: a review." Progress in Oceanography **69**(2): 239-266.

Wang, C. and J. Picaut (2004). "Understanding ENSO physics—A review." Earth's Climate: 21-48.

Wang, G. and H. H. Hendon (2007). "Sensitivity of Australian rainfall to inter-El Nino variations." Journal of Climate **20**(16): 4211-4226.

Wannebo, A. and C. Rosenzweig (2003). "Remote sensing of US cornbelt areas sensitive to the El Ni@ o-Southern Oscillation." International Journal of Remote Sensing **24**(10): 2055-2067.

Ward, P. J., et al. (2014). "Strong influence of El Niño Southern Oscillation on flood risk around the world." Proceedings of the National Academy of Sciences **111**(44): 15659-15664.

Wassmann, R., et al. (2009). "Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation." Advances in Agronomy **102**: 91-133.

Webster, P. J., et al. (1998). "Monsoons: Processes, predictability, and the prospects for prediction." Journal of Geophysical Research: Oceans (1978–2012) **103**(C7): 14451-14510.

Webster, P. J. and S. Yang (1992). "Monsoon and ENSO: Selectively interactive systems." Quarterly Journal of the Royal Meteorological Society **118**(507): 877-926.

Weiher, R. F. (1999). Improving El Niño forecasting: the potential economic benefits, National Oceanic and Atmospheric Administration, Office of Policy and Strategic Planning.

Wheeler, T. R., et al. (2000). "Temperature variability and the yield of annual crops." Agriculture, Ecosystems & Environment **82**(1): 159-167.

Wolde-Georgis, T., et al. (2010). "The Case of Ethiopia; the small rainy season in Ethiopia boosts during El Niño." Retrieved 3/06/2015, from http://archive.unu.edu/env/govern/ElNIno/CountryReports/pdf/ethiopia.pdf.

Woli, P., et al. (2015). "El Niño–Southern Oscillation Effects on Winter Wheat in the Southeastern United States." Agronomy Journal **107**(6): 2193-2204.

Wootton, J., et al. (1996). "Effects of productivity, consumers, competitors, and El Nino events on food chain patterns in a rocky intertidal community." Proceedings of the National Academy of Sciences **93**(24): 13855-13858.

World Bank (b). "World Bank Commodity Price Data (The Pink Sheet)." from http://go.worldbank.org/4ROCCIEQ50. (accessed September 2015).

World Bank(a) (2016). Rural population, World Bank.

Wyrtki, K. (1961). "Physical oceanography of the southeast Asian waters." Scripps Institution of Oceanography.

Wyrtki, K. (1975). "El Niño-The dynamic response of the equatorial Pacific oceanto atmospheric forcing." Journal of Physical Oceanography **5**(4): 572-584.

Wyrtki, K. (1977). "Sea level during the 1972 El Nino." Journal of Physical Oceanography **7**(6): 779-787.

Yokoyama, S. (2002). "ENSO Impacts on Food Crop Production and the Role of CGPRT Crops in Asia and the Pacific." Coping against El Nino for Stabilizing Rainfed Agriculture: Lessons from Asia and the Pacific: 79.

Yokoyama, S. (2010). "Historical Occurrence of El Nino and its Impact on Food Crop Production at a Regional Level in Asia and the Pacific."

Zanchettin, D., et al. (2008). "On ENSO impacts on European wintertime rainfalls and their modulation by the NAO and the Pacific multi-decadal variability described through the PDO index." International Journal of Climatology **28**(8): 995-1006.

Zhang, R., et al. (1999). "A diagnostic study of the impact of El Nino on the precipitation in China." Advances in Atmospheric Sciences **16**(2): 229-241.

Zhang, T., et al. (2008). "Correlation changes between rice yields in North and Northwest China and ENSO from 1960 to 2004." Agricultural and Forest Meteorology **148**(6): 1021-1033.

Zopf, D., et al. (1978). "Historical trends and statistics of the Southern Oscillation, El Niño and Indonesian droughts." Fish. Bull **76**: 663-678.

Zubair, L. (2002). "El Nino–southern oscillation influences on rice production in Sri Lanka." International Journal of Climatology **22**(2): 249-260.

Appendix

Table A.1. The full list of the countries of study

Country /Region	Code	Country /Region	Code
South Asia			
Afghanistan	AFG	India	IND
Bangladesh	BGD	Iran	IRN
Nepal	NPL	Sri Lanka	LKA
Pakistan	PAK		
South East Asia			
Cambodia	KHM	Myanmar	MMR
Indonesia	IDN	Philippines	PHL
Lao People's Democratic Republic	LAO	Thailand	THA
Malaysia	MYS	Viet Nam	VNM
East Asia			
China	CHN	Japan	JPN
Republic of Korea	KOR	Democratic People's Republic of Korea	PRK
West Asia			
Iraq	IRQ	Syrian Arab Republic	SYR
Saudi Arabia	SAU	Turkey	TUR
Africa			
Algeria	DZA	Morocco	MAR
Cote D'Ivoire	CIV	Mozambique	MOZ
Democratic Republic of Congo	COD	Nigeria	NGA
Egypt	EGY	Senegal	SEN
Ethiopia	ETH	Sierra Leone	SLE
Ghana	GHA	South Africa	ZAF
Guinea	GIN	United Republic of Tanzania	TZA
Kenya	KEN	Tunisia	TUN
Madagascar	MDG	Uganda	UGA
Malawi	MWI	Zambia	ZMB
Mali	MLI	Zimbabwe	ZWE
South America			
Argentina	ARG	Ecuador	ECU
Bolivia	BOL	Guyana	GUY
Brazil	BRA	Paraguay	PRY
Chile	CHL	Peru	PER
Colombia	COL	Uruguay	URY
Cuba	CUB	Venezuela	VEN
North America, central America and Caribbean			
Canada	CAN	Mexico	MEX
Dominican Republic	DOM	Nicaragua	NIC
Guatemala	GTM	United States of America	USA
Europe			
Austria	AUT	Italy	ITA
Bulgaria	BGR	Netherlands	NLD
Denmark	DNK	Poland	POL
France	FRA	Romania	ROU
Germany	DEU	Spain	ESP
Greece	GRC	Sweden	SWE
Hungary	HUN	United Kingdom	GBR
Oceania			
Australia	AUS		

Table A.2. Coefficients estimated by the ENSO effect on wheat production (1)

Country Code	El Niño	La Niña (2)	Temperature	Precipitation	(Precipitation)^2	log (Area)	log (price)
IND	*0.004*	*-0.025*	*-0.024*	*0.004*	*-0.00002*	*1.36 (***)*	*-0.11 (**)*
NPL	*0.013*	*0.006*	*0.057*	*0.006*	*-0.00001*	*0.72 (***)*	*0.05*
BGD	*-0.033*	*0.0004*	*0.142*	*-0.005*	*0.00001*	*1.23 (***)*	*0.102*
PAK	*-0.013*	*-0.003*	*0.015*	*0.0009*	*-0.000001*	*1.5 (***)*	*0.06 (*)*
AFG	*0.04*	*0.065*	*0.037*	*0.063*	*-0.002*	*1.21 (***)*	*0.18*
IRN	*0.018*	*0.036*	*0.011*	*0.039 (***)*	*-0.0005 (***)*	*0.75 (***)*	*-0.05*
CHN	*0.03*	*0.005*	*-0.024*	*0.022*	*-0.0001*	*1.31 (***)*	*0.01*
TUR	*-0.036*	*0.027*	*-0.018*	*-0.015*	*0.0002*	*1.15 (**)*	*0.03*
SYR	*-0.042*	*0.148* (*)	*-0.055*	*0.011*	*-0.00004*	*1.18 (***)*	*-0.07*
SAU	*0.045*	*0.085* (*)	*0.076 (*)*	*-0.075*	*0.004*	*1.25 (***)*	*0.2 (**)*
IRQ	-0.087	*0.192*	*-0.025*	*-0.025*	*0.0008 (**)*	*0.78 (***)*	*0.26*
USA	*0.049* (**)	*-0.002*	*-0.036 (**)*	*0.024 (**)*	*-0.0002 (**)*	*1 (***)*	*-0.04*
MEX	*-0.035*	*-0.001*	*-0.063*	*-0.02*	*0.0001*	*0.97 (***)*	*0.08*
CAN	*-0.07*	*0.151* (*)	*-0.013*	*0.03 (***)*	*-0.0002 (**)*	*0.88 (***)*	*0.05*
BRA	*-0.144*	*-0.058*	*-0.08*	*0.009*	*-0.00003*	*0.89 (***)*	*-0.01*
ARG	*0.111* (**)	*-0.085* (*)	*-0.011*	*0.018*	*-0.0001*	*1.14 (***)*	*0.05*
CHL	*0.015*	*-0.015*	*0.029*	*-0.005*	*0.00002*	*1.32 (***)*	*-0.25 (**)*
EGY	*0.028*	*-0.055* (**)	*-0.014*	*0.303*	*-0.041*	*1.25 (***)*	*-0.09*
DZA	*-0.068*	*-0.06*	*0.014*	*-0.007*	*0.0002 (*)*	*1.33 (***)*	*-0.24 (**)*
ETH	*0.003*	*0.028*	*0.062*	*-0.031 (**)*	*0.0002 (**)*	*0.81 (***)*	*0.03*
TUN	*0.002*	*0.039*	*-0.011*	*0.016*	*-0.0002*	*1.09 (***)*	*-0.03*
ZAF	*0.061*	*-0.136* (***)	*-0.02*	*-0.021*	*0.00023*	*0.82 (***)*	*-0.05*
MAR	*-0.264* (**)	*0.171*	*0.146 (*)*	*0.003*	*0.0001*	*2.33 (***)*	*0.11*
ESP	*-0.029*	*-0.104* (**)	*-0.036*	*0.025*	*-0.0002*	*0.11*	*-0.27 (**)*
ITA	*0.026*	*-0.049* (**)	*-0.055 (**)*	*0.043 (***)*	*-0.0004 (***)*	*0.84 (**)*	*-0.06*
AUT	*0.059*	*-0.072* (**)	*-0.025*	*0.011*	*-0.00006*	*1.2 (***)*	*0.003*
FRA	*-0.002*	*-0.039* (**)	*-0.028 (**)*	*0.021 (***)*	*-0.0002 (***)*	*1.4 (***)*	*-0.05*
DEU	*-0.01*	*-0.025*	*-0.019 (*)*	*0.027 (***)*	*-0.0002 (***)*	*0.7 (***)*	*-0.07 (**)*
GRC	*-0.084*	*-0.048*	*-0.055 (**)*	*0.014*	*-0.0001*	*0.88 (***)*	*-0.01*
HUN	*0.015*	*-0.071* (**)	*-0.067 (**)*	*0.015*	*-0.0001*	*1.55 (***)*	*-0.02*
POL	*0.008*	*-0.035*	*-0.022*	*0.004*	*-0.00003*	*0.99 (***)*	*0.06*
ROU	*-0.053*	*-0.036*	*-0.093 (***)*	*0.018 (**)*	*-0.0001 (**)*	*1.63 (***)*	*-0.004*

Table A.2. Continued coefficients estimated by the ENSO effect on wheat production (1)

Country Code	El Niño	La Niña (2)	Temperature	Precipitation	(Precipitation)^2	log (Area)	log (price)
GBR	0.008	0.004	-0.041 (**)	0.007	-0.0001	1.51 (***)	-0.04
NLD	0.035	0.015	-0.037 (**)	-0.003	0.000003	0.999 (***)	-0.04
SWE	-0.044	-0.051	0.019	0.0029	-0.00001	1.09 (***)	0.02
DNK	-0.01	-0.033 (**)	0.005	0.017 (*)	-0.0002 (*)	1.11 (***)	0.07
BGR	-0.134 (**)	0.026	-0.058 (*)	0.038 (**)	-0.0003 (*)	0.83 (***)	0.08
AUS	-0.084	0.043	-0.07	0.162 (***)	-0.002 (***)	0.9 (***)	-0.04

(1) The dependent variable is the natural logarithm of wheat production.

(2) Since the SSTA during La Niña phase development is negative, to facilitate comparisons in previous chapters the sign of the parameters associated with la Niña has been reversed.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

The results of this study show that price and crop production are positively correlated in most countries. The positive effects may indicate that following an increase in expected price applying productive management practices by farmers (Feng and Babcock 2010), leads to an increase in yield (Miao, Khanna et al. 2016). Alternatively, rising prices may encourage farmers to increase the planting area and even plant low quality fields, which results in lower overall productivity (Feng and Babcock 2010, Miao, Khanna et al. 2016). Plant growth increases approximately linearly in temperature and precipitation up to a point where additional heat and precipitation become unfavourable (Schlenker and Roberts 2008). Also, the results of this study confirm the negative relationships between the quadratic terms of precipitation and crop production in most of the countries. The negative relationship between temperature and production may go back to the intervention impact of precipitation (Anderson and Finn 2012). This means that when temperature is low, there is a tendency for higher rainfall to occur, which partially offsets the unfavourable impact of low temperature.

Table A.3. Coefficients estimated by the ENSO effect on maize production (1)

Country Code	El Niño	La Niña(2)	Temperature	Precipitation	(Precipitation)^2	log (Area)	log (price)
IDN	0.006	0.011	-0.0003	-0.0003	-0.0000004	1.18 (***)	-0.043
PHL	-0.04 (*)	-0.001	0.022	0.001	-0.000002	1.05 (***)	0.007
VNM	-0.032	-0.036	0.028	-0.006	0.00001	0.7 (***)	-0.059
THA	-0.051	-0.051 (*)	-0.043	0.012 (**)	-0.00002 (**)	0.54 (***)	0.094
IND	-0.045	0.007	-0.053	-0.006	0.00001	0.64 (***)	-0.001
NPL	-0.009	0.003	-0.018	0.0004	-0.000001	1.03 (***)	0.115 (***)
PAK	0.027	0.004	0.061	0.01 (**)	-0.0001 (*)	1.52 (***)	0.278 (***)
IRN	0.133 (*)	-0.119	-0.009	-0.005	0.0002	0.97 (***)	0.026
CHN	-0.026	0.011	-0.007	0.009	-0.00003	0.99 ***	0.008
PRK	-0.227	0.044	-0.021	0.014	-0.00004	3.26 (***)	-0.745 (**)
TUR	-0.046	-0.025	-0.109 (***)	0.005	-0.00008	0.46	-0.128
USA	0.027	0.012	-0.031 (**)	0.029 (***)	-0.00013 (**)	1.73 (***)	-0.178 (***)
MEX	0.004	0.06 (**)	-0.026	-0.005	0.00001	1.04 (***)	-0.048
CAN	0.023	0.036	0.085 (***)	0.01	-0.00006	0.97 (***)	0.075
VEN	-0.028	0.003	-0.057 (*)	0.01	-0.00003	0.83 (***)	-0.18 (***)
BRA	-0.01	-0.037 (**)	0.034	0.02	-0.00004	1.001 (***)	-0.001
ARG	-0.028	0.046	-0.072 (**)	0.006	-0.00001	1.16 (***)	0.026
CHL	0.034	0.013	-0.023	0.05	-0.003	0.97 (***)	-0.229 (**)
PER	0.0167	0.023	-0.055 (*)	0.004	-0.00002	1.33 (***)	0.017
PRY	-0.036	0.002	0.025	0.008 (*)	-0.00002	0.92 (***)	-0.002
COL	-0.004	0.018	-0.014	0.005	-0.00001	0.75 (***)	0.069
GTM	-0.019	-0.036	0.034	0.003	-0.000004	0.66 (***)	0.189
EGY	0.017	-0.004	0.036 (*)	0.18	-0.0618	0.28	-0.052
ETH	-0.009	-0.025	0.205 (**)	-0.01	0.0001	0.6 (***)	-0.063
NGA	-0.073	-0.053	0.02	0.02	-0.00004	0.85 (***)	-0.141
MWI	-0.126	-0.129 (*)	0.303 (***)	0.006	-0.000003	0.7 (*)	0.031
GHA	-0.003	0.03	0.004	0.027	-0.00008	0.92 (***)	0.009
KEN	-0.018	0.021	-0.039	0.045 (***)	-0.0002 (**)	0.88 (***)	-0.116 (*)
COD	0.017 (*)	-0.003	-0.014	0.004	-0.00001	0.93 (***)	-0.049
ZAF	-0.197 (**)	0.07	-0.039	0.052 (***)	-0.00029 (**)	1.001 (***)	0.373 (**)
TZA	-0.06	-0.052	0.077	0.038 (*)	-0.0001 (*)	0.421 (***)	-0.154

Table A.3. Continued coefficients estimated by the ENSO effect on maize production (1)

Country Code	El Niño	La Niña (2)	Temperature	Precipitation	(Precipitation)^2	log (Area)	log (price)
MOZ	0.066	-0.041	0.038	0.028	-0.0001	0.04	0.145
ZMB	-0.143	0.11 (**)	-0.062	0.039 (*)	-0.0001	0.8 (***)	0.085
ZWE	-0.135	-0.048	0.018	0.042 (***)	-0.00015 (***)	0.66 (**)	-0.273 (*)
UGA	-0.044	-0.103	0.084	0.002	-0.00001	0.99 (***)	0.109
ESP	0.019	-0.033	-0.029	-0.0005	-0.00001	1.26 (***)	-0.049
ITA	0.003	-0.044 (*)	-0.022	0.012	-0.00006	1.25 (***)	0.048
AUT	0.01	-0.006	0.024	0.027	-0.00011 (**)	1.19 (***)	0.012
BGR	0.055	0.097	-0.009	0.034	-0.0001	1.02 (**)	-0.01
FRA	0.028	0.029	0.004	0.021	-0.0001	1.15 (***)	-0.052
DEU	0.012	-0.033	0.018	0.046 (***)	-0.0003 (***)	1.08 (***)	0.001
GRC	-0.018	0.034	-0.03	-0.019 (**)	0.0003 (**)	1.5 (***)	0.05
HUN	0.078	-0.046	-0.044	0.035 (*)	-0.0002 (*)	1.21 (***)	0.032
POL	0.051	-0.161 (***)	0.027	0.015	-0.00008	1.12 (***)	0.169
ROU	-0.021	0.072 (*)	-0.024	0.036 (**)	-0.0002 (*)	1.14 (**)	-0.063

(1) The dependent variable is the natural logarithm of wheat production.

(2) Since the SSTA during La Niña phase development is negative, to facilitate comparisons in previous chapters the sign of the parameters associated with la Niña has been reversed.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

The results of this study show that price and crop production are positively correlated in most countries. The positive effects may indicate that following an increase in expected price applying productive management practices by farmers (Feng and Babcock 2010), leads to an increase in yield (Miao, Khanna et al. 2016). Alternatively, rising prices may encourage farmers to increase the planting area and even plant low quality fields, which results in lower overall productivity (Feng and Babcock 2010, Miao, Khanna et al. 2016). Plant growth increases approximately linearly in temperature and precipitation up to a point where additional heat and precipitation become unfavourable (Schlenker and Roberts 2008). Also, the results of this study confirm the negative relationships between the quadratic terms of precipitation and crop production in most of the countries. The negative relationship between temperature and production may go back to the intervention impact of precipitation (Anderson and Finn 2012). This means that when temperature is low, there is a tendency for higher rainfall to occur, which partially offsets the unfavourable impact of low temperature.

Table A.4. Coefficients estimated by the ENSO effect on rice production (1)

Country Code	El Niño	La Niña (2)	Temperature	Precipitation	(Precipitation)^2	log (Area)	log (price)
IDN	-0.037 (***)	-0.009	0.003	0.00002	-0.000002	1.17 (***)	-0.02
MYS	0.005	0.02	-0.089 (**)	0.001	-0.000001	1.43 (***)	0.08 (***)
PHL	-0.032	0.048 (**)	-0.043	-0.001	0.000001	0.78 (***)	-0.04
VNM	0.013	-0.072 (**)	0.021	0.016 (**)	-0.00003 (**)	0.91 (***)	-0.14 (***)
KHM	0.013	-0.147 (**)	-0.129 (***)	0.006	-0.00002	1.24 (***)	0.06
THA	-0.007	-0.015	-0.011	0.002	-0.000002	0.81 (***)	-0.04 (***)
MMR	-0.011	0.02	0.027	0.003	-0.000004	0.64 (*)	-0.04
LAO	-0.025	-0.035	0.007	0.011	-0.00002	0.74 (***)	-0.07
LKA	0.001	0.037	0.001	-0.0004	0.0000007	0.98 (***)	-0.05
IND	0.006	0.006	-0.053	0.011 (*)	-0.00002 (*)	2.28 (***)	-0.07 (***)
BGD	-0.029 (**)	0.006	0.005	0.005 (**)	-0.00001 (**)	1.26 (***)	-0.03
NPL	-0.035	-0.005	-0.042	-0.003	0.000005	2.5 (***)	-0.02
PAK	0.02	-0.058	0.027	0.001	-0.000009	1.59 (***)	0.04
AFG	0.037	0.003	0.044 (*)	-0.018	0.001 (*)	0.81 (***)	0.2 (***)
IRN	0.015	0.0006	-0.028	0.006	-0.0001	1.1 (***)	-0.02
JPN	0.008	-0.008	0.047 (***)	0.005 (***)	-0.00001 (***)	0.97 (***)	0.04 (**)
CHN	0.015	-0.008	-0.017	-0.002	0.000005	0.55 (**)	-0.02
KOR	0.003	0.002	0.041	0.0005	-0.000002	1.44 (***)	0.06
PRK	-0.123 (*)	0.032	-0.062	0.016	-0.00004	0.08	0.13
TUR	-0.016	-0.029	-0.057 (**)	0.007	-0.0001	1.02 (***)	0.03
EGY	-0.009	-0.015	0.039 (**)	-0.067 (*)	0.011	1.22 (***)	-0.07 (***)
SLE	0.02	0.025	-0.098 (**)	-0.011	0.00001	1.04 (***)	0.17 (**)
NGA	0.041	0.032	0.136 (**)	0.016	-0.00003	0.99 (***)	0.21 (***)
MDG	0.011	0.009	-0.058	0.002	-0.000004	0.76 (***)	0.06
GHA	-0.06	0.022	-0.077	0.015	-0.00004	0.68 (***)	-0.02
MLI	0.009	0.027	-0.145	0.058 (*)	-0.00031 (*)	0.68 (***)	0.02
COD	0.009	0.018	-0.02	0.006	-0.00001	0.939 (***)	0.02
GIN	0.003	0.004	-0.015	-0.001	0.0000009	0.87 (***)	0.02 (*)
TZA	-0.125	-0.116	0.076	0.039 (***)	-0.00017 (***)	0.68 (***)	-0.28 (*)
CIV	-0.051 (**)	0.016	-0.089 (**)	0.012 (**)	-0.00003 (*)	0.38 (***)	0.04
SEN	-0.027	0.064	0	0.006	-0.000006	1.05 (***)	-0.08
USA	0.004	-0.004	-0.031 (***)	-0.001	0.000008	0.87 (***)	-0.04 (**)
MEX	0.005	0.028	-0.007	-0.002	0.000006	0.9 (***)	0.02
CUB	-0.083	-0.026	-0.021	0.012	-0.00003	0.99 (***)	-0.05

Table A.4. Continued coefficients estimated by the ENSO effect on rice production (1)

Country Code	El Niño	La Niña (2)	Temperature	Precipitation	$(\text{Precipitation})^2$	log (Area)	log (price)
NIC	0.107 (**)	0.065 (**)	-0.113 (**)	0.007 (*)	-0.00001	0.9 (***)	0.04
DOM	0.045	0.005	-0.07 (**)	0.003	-0.00001	0.64 (***)	-0.08
VEN	-0.046	0.006	0.106	0.007	-0.00001	0.76 (***)	0.22 (**)
BRA	-0.045 (**)	-0.036	0.01	-0.006	0.00001	0.84 (***)	-0.08 (**)
ARG	0.059	-0.024	0.009	0.001	-0.00001	1.12 (***)	-0.003
BOL	-0.006	-0.028	0.043	-0.004	0.00001	0.87 (***)	0.06
PER	-0.045	-0.009	0.004	0.01 (*)	-0.0001	1.1 (***)	-0.01
ECU	-0.012	0.048	0.001	0.003	-0.00001	0.8 (***)	0.02
URY	0.003	-0.038	0.088	0.001	-0.00001	0.99 (***)	0.06
COL	0.069	-0.022	-0.104	0.009	-0.00002	0.74 (***)	0.03
GUY	-0.025	0.033	0.026	-0.002	0.000004	1.06 (***)	-0.08
ESP	-0.021 (*)	-0.0002	0.008	-0.001	0.00003	1.16 (***)	-0.008
ITA	-0.02	-0.009	0.074 (**)	0.002	-0.000012	0.65 (***)	0.08 (*)
AUS	0.052	-0.036	0.081 (***)	0.006	-0.0001	1.06 (***)	-0.11 (***)

(1) The dependent variable is the natural logarithm of wheat production.

(2) Since the SSTA during La Niña phase development is negative, to facilitate comparisons in previous chapters the sign of the parameters associated with la Niña has been reversed.

(*), (**) and (***) indicate the significant impact at 10%, 5% and 1% level of significant, respectively.

The results of this study show that price and crop production are positively correlated in most countries. The positive effects may indicate that following an increase in expected price applying productive management practices by farmers (Feng and Babcock 2010), leads to an increase in yield (Miao, Khanna et al. 2016). Alternatively, rising prices may encourage farmers to increase the planting area and even plant low quality fields, which results in lower overall productivity (Feng and Babcock 2010, Miao, Khanna et al. 2016). Plant growth increases approximately linearly in temperature and precipitation up to a point where additional heat and precipitation become unfavourable (Schlenker and Roberts 2008). Also, the results of this study confirm the negative relationships between the quadratic terms of precipitation and crop production in most of the countries. The negative relationship between temperature and production may go back to the intervention impact of precipitation (Anderson and Finn 2012). This means that when temperature is low, there is a tendency for higher rainfall to occur, which partially offsets the unfavourable impact of low temperature.